An Investigation into Modularity-in-Context and 3D Printing for Resource Integration: An Operations Management Perspective

By

Philip Michael Davies

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Declaration

This thesis is presented in accordance with the regulations for the degree of Doctor of Philosophy. It has been written by myself and has not been submitted in any previous application for any degree. The work in this thesis has been undertaken only by the author.

Signed: Date:

Name: Philip Michael Davies

Abstract

Through a review of design, modularity and service-dominant logic literature, two design strategies were found to be prevalent within the literature; designing for low variety and designing for high variety. Whilst designing for low variety was found to be a mature phenomenon of interest, designing for high variety was emerging within the literature following advances in digital technologies and an understanding that value is co-created in use. Following three empirical studies, a theoretical understanding of designing for high variety as a process of resource integration has been developed that enables a greater understanding as to how organisations can design for contexts characterised by high variety and continuous change. From this understanding, it is possible to answer the question, why does designing for high variety have different requirements to designing for low variety?

The research addresses a number of gaps in the literature. First, the limitations of a designing for low variety within contexts characterised by high variety has not been empirically explored. Second, there is little theory associated with designing for high variety and resource integration. Third, why designing for high variety has different requirements to designing for low variety is a relatively understudied area in the literature, meaning no conceptual framework explaining the relationship between design and high variety exists.

Fieldwork was carried out over a two year period in a large capital goods supplier in the UK which resulted in three empirical studies. These studies resulted in a number of significant findings. The results of the first study present a number of research propositions, some of which contradict existing thinking around modularity theory. Study two then conducted a quantitative investigation to test the relationship between design change complexity, use complexity and system viability, with significant results for the moderating role of use complexity found. The final study introduces 3D printing and quantitatively shows that its use in designing for high variety would enable a firm to modify and adapt the affordance of the physical asset to support the customer in absorbing the variety with the physical asset as opposed to relying on human activities to absorb said variety. Furthermore, it shows the benefits of 3D printing in certain contexts when compared to traditional manufacturing.

From the three studies, a theoretical understanding of designing for high variety as a process of resource integration is developed. This provides a greater understanding as to how organisations can design for contexts characterised by high variety and continuous change. Namely, from the perspective of modularity, how can thin and thick crossing points be identified and created to allow the organisation to integrate resources at the point of use and allow the focal beneficiary to modify, tailor and adapt the organisations asset based upon their desired outcome in use. In addition, these findings allowed a mid-range theory for service-dominant logic to be derived.

Keywords: Modularity; Servitization; Service-Dominant Logic; 3D Printing; Resource Integration; Designing for high variety; Modularity-in-Context; Value in Use

Acknowledgements

This paragraph signifies the beginning of my thesis but also the end of an enlightening journey. During this time, I have learnt new things and overcome challenges I never thought I would be able to. Not only have I done this from a scholarly perspective, but also personally. To list all of the things I have learnt and challenges I have overcome would require more room than the little space I have here. Importantly, I could not have done them alone and it is the family, friends and colleagues I am so lucky to have that have made this journey not only possible, but enjoyable. In particular, I would like to thank the following people for their help, support and guidance throughout this journey:

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For my Grandparents

The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low and achieving our mark.

- Michelangelo

For my Uncle and Godfather

Twenty years from now, you will be more disappointed by the things you didn't do than those you did. So throw off the bowlines. Sail away from safe harbour. Catch the wind in your sails. Explore. Dream. Discover.

- Mark Twain

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List of Abbreviations

ASM - Activity Structure Matrix

CDE – Centre for Defence Enterprise

DEFSTAN – Defence Standard

DSM -Design Structure Matrix

DMM - Domain Mapping Matrix

FSR - Field Service Representative

GDP – Gross Domestic Product

G-D Logic – Goods Dominant Logic

IHIP – Intangible, Heterogeneous, Inseparable and Perishable

IoT – Internet of Things

MoD - Ministry of Defence

S-D Logic – Service Dominant Logic

PSS – Product Service System

UK – United Kingdom

UOR – Urgent Operational Requirement

Chapter 1. Introduction

1.1 Introduction

This thesis is about modularity as a foundational theory for resource integration and designing for high variety. This thesis begins by questioning whether existing modular systems theory is a suitable design approach for high variety contexts before generating a greater understanding of design and resource integration focussed on use and context where the organisation designs for high variety. Here, low variety refers to a focus on value in exchange, where the customers' use context is exogenous to the organisation's activities, designs are created against a fixed (snapshot of use) specification and context and design are separated by the organisation. Thus, the organisation assumes contextual variety is consistently low and predictable for their customers. In contrast, high variety is where the customers' context of use is endogenous to the organisation's activities, the focus is on value in context and context and design are entangled. Thus, the organisation recognises their customers' context of use are dynamic and emergent and any variety that emerges at the point of use needs to be managed and mitigated by the organisation and the customer together. In presenting a theory of modularity focussed on resource integration and high variety, where 3D printing can be used to temporarily bind form and function in use, this thesis contributes to the development of a mid-range theory for service-dominant (S-D) logic.

The context of this thesis is servitization, where it has long been understood that an organisation has a greater focus on resource integration for the purpose of co-creating value in use and the achievement of customer outcomes. Within this context, it has been argued that existing modular systems theory, described as a modularity for low variety within this thesis, is not suitable for contexts characterised by high variety and continuous change. In recognising this, the literature calls for empirical studies to generate a greater understanding as to the theoretical foundations of designing for high variety as a process of resource integration. Namely, the literature converges on a broader understanding of modularity theory, underpinned by service-dominant logic, as relevant to our understanding of designing for high variety.

Through a review of the literature and three empirical studies, this thesis develops a theoretical understanding as to why designing for high variety is fundamentally different to designing for low variety and how modularity can inform a foundational theory of designing for high variety as a process of resource integration.

The overarching theoretical research question for this thesis is as follows:

- Why does designing for high variety have different requirements to designing for low variety?

This chapter is structured as follows. First, current approaches to designing for high variety and modularity are briefly discussed. Second, it justifies the relevance and opportunity for operations management (OM). Third, the contribution to knowledge of this thesis is provided. Finally, the structure of this thesis is presented.

1.2 Current understanding of designing for high variety and modularity theory

This section briefly outlines the current understanding of designing for high variety and modularity theory, justifying the purpose of this thesis.

1.2.1 Current understanding of designing for high variety

Designing for high variety is an emergent concept within both research and practice. Simply, it is a design strategy that acknowledges the entanglement of design and context and emphasises resource integration to support value in context. Value in context is a broadened view of value creation that moves beyond the focal firms' operations to include the participation of other actors within the service system (Lusch & Vargo, 2014). This shifts our understanding of value away from being produced in a linear and sequential manner prior to its destruction by the customer during use (Vargo & Lusch, 2004) toward a more dynamic and complex process of value co-creation that is relationally co-created during the contextually determined use and experience of the offering (Lusch & Vargo, 2014). In this instance, the focus of the organisation is to act an input to the customers' use context and continually readjust resources available in use to support the customers' value co-creating activities (Ng, 2013; Lusch & Vargo, 2014). The former, sequential understanding of value aligns with a designing for low variety strategy where the customer and their context are exogenous to the organisation's operational activities (i.e., value in exchange and a G-D logic), whilst value in context as dynamic, complex and ever-changing aligns with designing for high variety where the customer and their context are endogenous to the organisation's operational activities (i.e., value in context and a S-D logic). Thus if we were to compare the two strategies, designing for low variety would emphasise value-in-exchange, fixed functional boundaries (i.e., once produced the offering has limited ability to be functionally reconfigured) and be suitable for organisations whose customers' contexts of use were fairly repeatable and predictable. In contrast, designing for high variety would emphasise value-in-context, fluid functional boundaries and be suitable for organisations whose customers' contexts of use were fairly dynamic and unpredictable. This is expanded upon in chapters 2 and 4.

Whilst the concept of designing for high variety has been discussed as a simple concept, a number of complexities emerge given the concept is not well defined theoretically. Despite the literature aligning with modularity theory and service-dominant logic (S-D), the concept remains theoretically shallow and incomplete. However, the literature does align on a few general characteristics of designing for high variety. These are value in use, resource integration at the point of use (i.e, the customers' context) and 3D printing and the Internet of Things (IoT) as enabling technologies. In particular, the literature positions designing for high variety as being suited to different business contexts when compared with designing for low variety.

Within practice, whilst few tangible examples of designing for high variety exist, the practitioner sphere does share common thought with the academic community in that designing for high variety is enabled by digital technology and would allow customers' to tailor, adapt and modify equipment in use for the purpose of value creation. An example from industry can be found in the defence industry where the US Department of Defence (DoD) are investigating the use of 3D printing for resource (re) configuration at the point of use (i.e., within conflict zones). This is illustrated in figure 1.1.

Figure 1.1. Deloitte and DoD 3D printing concept (Source: Deloitte).

Within figure 1.1, Deloitte and the DoD conceptualise 3D printing being used within conflict zones, reflecting the concept of product instances discussed by Holmstrom & Partenan (2014). Whilst futuristic, they maintain that it is a real possibility with a number of implications. These being resources customised to individual customer requirements in use, service business model innovation, supply chain innovation and manufacturing within the customers' context of use. Within all four of these components, it is evident that both design and operations are at the heart of the concept.

The fact that designing for high variety is being recognised by both industry and practice suggests that it is becoming an increasingly important and relevant topic. Through a greater understanding of the theoretical underpinnings of designing for high variety as a process of resource integration, it is anticipated that new insights into design and operations will be provided that are beneficial for both academia and practice respectively. Furthermore, it will be increasingly important for the exploitation of digital technologies for the benefit of customers' in use. Based on this discussion, it is possible to justify the purpose of this thesis in theoretically developing the concept of designing for high variety.

1.2.2 Current understanding of modularity

Modularity is currently understood as a strategy for organising complex products and processes efficiently (Baldwin & Clark, 2000). Primarily studied within the context of physical products, modularity advocates efficiency in design and production through the loose coupling between modules that comprise the whole system. At the heart of this theory is the idea that modules can be mixed and matched and recombined into a number of different configurations (Schilling, 2000). The ability to mix and match components, that can be defined as resources more broadly, is defined in the design stage, where the architecture is frozen for the purpose of creating efficiency in design and production. Therefore, current strategies focus on creating flexibility in the design stage and proposing a number of different product types (product variety) at the point of exchange. Notably, the design role within this understanding of modularity is to decompose a product so that form and function can be bound and allocated to specific design hierarchies before the actual use of the offering (Yoo, 2013). Therefore, modularity in its current form focusses on differences in degree (Yoo, 2013).

Recently, modularity has been conceptualised more broadly as allowing the efficient exchange of material, energy and information between two exchanging parties (Baldwin, 2008). At this level of conceptualisation, a stronger understanding of modularity for resource integration has emerged. However, this theory has only been illustrated in simplistic production chain examples (Spring & Araujo, 2009). The use of these simplistic examples hides the complexity in how resource integration actually takes place in dynamic, kinetic and emergent systems of exchange (Ng, 2013). In the context of this thesis, complexity is defined as non-simple interactions between interdependent resources within a complex system (Simon, 1996), where a complex system is one made up of a number of interdependent parts which, when combined, make up the whole (Parry, 2008). Despite these advances, modularity as a process remains a relatively recent phenomenon and existing theoretical insights are limited, especially in the context described by Ng (2013).

1.3 Relevance and opportunity for operations management

Since this work is concerned with understanding design as a process of resource integration, it is important to understand the process concept that is central to OM

(Holweg et al, 2018). For OM, all operations focus on input-transformation-output processes and that the role of the operations manager is to evaluate and improve the activities contained within this process (Slack et al, 2015). Figure 1.2 illustrates this process.

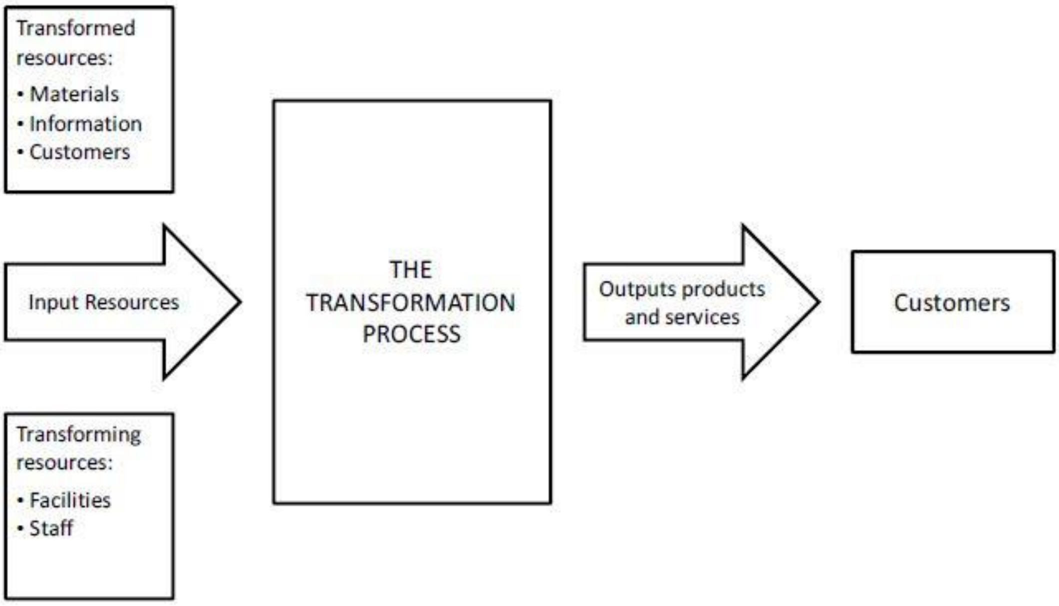

Figure 1.2. The input-transformation-output process.

Within figure 1.2, there are three main resource types that can be transformed during the process by staff or facilities; material, information and customers (Morris & Johnston, 1987). Whilst OM has inherently been associated with material transformation, service operations management highlights how all three resources can be inputs into the process (Morris & Johnston, 1987; Sampson & Froehle, 2006). The purpose of all operations is to create and deliver products and services by transforming inputs into outputs using the process illustrated in figure 1.2 (Slack et al, 2015).

It is possible to ground resource integration, as defined by service-dominant (S-D) logic, within this process. That is, resource integration is the process through which actors integrate and transform micro-specialised competencies (either directly or indirectly (through a product or tangible resource)) that perform specific functions for a specific actor and for the purpose of value co-creation and the joint achievement of outcomes (Vargo & Lusch, 2008). More specifically, operant (knowledge and skills of actors) act upon operand (material resources) or other operant resources in the process to create an effect (an outcome). However, the act and process of resource integration as defined from a S-D logic perspective is more dynamic and emergent than the process illustrated in figure 1.2 and emphasises the transformation of resources to support the achievement of outcomes for the focal beneficiary, as opposed to the production of a unit of output within the organisations production activities. Importantly, Hayes (2002; 2008) calls for the OM community to move beyond static products and processes to a more dynamic and ecosystem orientated understanding of products and processes in the new economy (information and digital economy). Within this thesis, it is argued that this aligns closer to a S-D logic. From this perspective, the boundary of the process of resource integration moves beyond the organisations manufacturing or service business unit and into the focal beneficiaries context of use. This suggests it is not just staff or facilities of the organisation transforming resources for whom they have control over, but also the customer for the achievement of outcomes. Whilst a subtle difference, it has implications for the organisation as their operations become focussed on use and supporting the customer in co-creating value and transforming resources for the achievement of outcomes.

Whilst the process concept has been shown to be central to OM and S-D logic, it has also amassed significant interest within modularity theory. Process has not been the main focus of modularity theory since its emergence in the 1960s, but has recently been recognised as central when Baldwin (2008) conceptualised modularity as enabling the efficient exchange of resources between different parties. As discussed in section 1.2.2, it is argued that resource integration takes place most efficiently at module boundaries (Ng, 2013) and that this is extremely important for product and process design within OM (Spring & Araujo, 2009). Importantly, it is found that resources are transformed and acted upon within modules for the output to then be exchanged at the boundary of said module for another actor or module to integrate and act upon for the co-creation of value. This process aligns with the description of design presented by Garud et al (2008) which is discussed in more detail in chapter 2 and 3. Ng (2013) argues this process orientated view of modularity is foundational to our theoretical understanding of designing for high variety. Whilst it has received significant interest in the past decade, it can be argued this concept is still relatively immature. That said, modularity theory offers valuable insights into designing for high variety and the process of resource integration. Modularity is reviewed within the chapter 2 and 3.

This brief introduction to the process concept within OM highlights its relevance to this thesis. Whilst similarities have been identified, it presents an opportunity to advance OM in an increasingly digitised and connected world where processes occur within dynamic and emergent service ecosystems that emphasise outcomes over outputs and value in use over value in exchange.

1.4 Contributions to knowledge

This thesis has made a number of contributions to knowledge. These will be addressed in detail in chapter 11. That said, it is possible to summarise the most notable contributions here.

First, a number of differences between designing for high variety and designing for low variety were found within the literature and the empirical studies. This addresses a number of gaps in the literature. Notably, it provides a theoretical foundation to explore the difference between the two design strategies as well as provide a foundation for developing a theoretical understanding as to designing for high variety. It also addresses the gap in the literature that calls for greater research surrounding the design of the physical asset within servitization and in addressing this gap, it provides empirical support for a number of claims in the literature that the physical asset may be contributing to the service paradox.

Second, the findings identify some limitations with existing modularity literature that suggests it is a design strategy that allows modules to evolve autonomously without increasing the complexity of the system. Instead, the findings showed that when design changes that were not part of the original design specification are integrated, the level of design complexity increases within the products architecture. In finding this it also contributed to the servitization literature that questioned whether functionally rigid assets contribute to the service paradox when deployed within high variety contexts.

Finally, this thesis has contributed to the development of a mid-range theory for S-D logic within OM. Namely, this thesis has drawn upon the foundational premise of S-D logic and its principles not only to reconceptualise design for high variety, but to alter the focus of design on resource integration and the customers' context of use. Within the customer's context of use, the role of the organisation is to constantly readjust resources in use to absorb contextual variety and support the co-creation of value in context.

1.5 Scope of thesis

Simply, this thesis is interested in understanding designing for high variety from the perspective of the customers' context, where integration of the firms' material or digital assets occurs away from the organisation. Here, a face to face interaction between the two parties is not a pre-requisite and the material asset is the focal point of the organisations service offering. An example would be product centric servitization (Baines et al, 2009a) where the organisations asset resides within the customers' context of use and the organisation themselves are not present in context when the customer uses the asset to co-create value. An example of designing for high variety that is within the scope of this thesis was presented in section 1.2.1. Thus, whilst a number of interesting articles have been published in the context of traditional services contexts (e.g., healthcare, finance and tourism), these settings and associated value propositions are not within the scope of this thesis.

1.6 Structure of this thesis

The thesis is presented in eleven chapters. The remainder of this thesis is organised as follows.

Chapter two, three and four review the literature paying particular attention to the design and modularity literature, service-dominant logic literature and servitization literature. Chapter five condenses the findings from the literature into a number of broad themes that are used within the empirical chapters to guide the data collection. Chapter six summarises the literature review, presenting the knowledge gaps, research objective and research question. Chapter seven justifies the choice of critical realism to guide this research, the choice of a single case study research design and presents the primary data collection techniques. Chapter eight, nine and ten present the three empirical components of this thesis. Finally, chapter eleven concludes the thesis with a summary of the major discussion points, its contribution to knowledge, managerial implications, limitations and future research opportunities.

Chapter 2. Design and Modularity: A Literature Review

2.1 Introduction

This chapter reviews the existing literature with respect to current design approaches, with particular attention paid to modular design. The purpose of this is to identify contributions towards the emerging phenomenon of designing for high variety. To do this, both the existing literature focussing on designing for low variety and the contemporary literature focussing on designing for high variety are analysed. The aim of this chapter is to highlight how design is moving toward a process of resource integration, enabled by digital technology, which is focussed on the customers' context of use and value in use as described in chapter 1.

This chapter is structured as follows. First, designing for low variety and designing for high variety are discussed before existing knowledge around designing for low variety is illustrated in the context of modular design. Second, designing for high variety is discussed in greater detail before three examples from the literature are presented. Third, contributions toward understanding designing for high variety as a process of resource integration are discussed. Finally, a summary of the key findings conclude the chapter.

2.2 Designing for low and high variety

According to the Oxford English Dictionary, design is '*a plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made'.* Within OM, design is a broad concept that can be discussed with respect to product and service design or process design. This is captured by Slack et al (2015) who define design as "*the process by which some functional requirement of people is satisfied through the shaping or configuration of the resources and/or the activities that comprise a product, or a service, or the transformation process that produces them" (*pp. 96*).* Within the literature, design is seen more specifically as a knowledge intensive activity focussed on the development of new products or services, acting as the stage between upstream research and development activities and downstream manufacturing and operations design (Hong et al, 2005). This definition corresponds with Rungtusanatham & Forza (2005) who suggest design is a conceptual activity and manufacturing is the creation of that design. This distinction also underpins our understanding of design within the modularity literature. For modularity, the conceptual component of design is often discussed with respect to a products architecture, where the architecture created by the designer is defined as a description of the modules, associated functions and the interfaces that connect them to allow the product, once produced, to function as an integrated whole (Ulrich & Eppinger, 2000; Baldwin & Clark, 2000; Schilling, 2000). Furthermore, the modularity literature makes a distinction between modularity in design, where the architecture is specified, and modularity in production, where the design is produced. The former relates to product modularity and the latter process modularity (Starr, 1965; Vickery et al, 2016).

Traditionally, within both product and service design, the role of the designer is to transform a set of user requirements and performance attributes into a specification of both material and immaterial properties for the value proposition (Ulrich & Pearson, 1998; Goldstein et al, 2002; Garud et al, 2008) with the specification allowing the designer to decompose the product into a smaller set of components whose form and function is bound prior to production and use (Yoo, 2013). Inherent in this understanding of design is the notion of 'completeness' where a clear boundary between design and the context within which the design is supposed to operate is created (Garud et al, 2008). The boundary is represented in figure 2.1 where the number 1 indicates the design realm and number 2 the context. This understanding of completeness is also reflected in the modular design literature where Baldwin & Clark (2000) state that the designer requires a *"complete description of structural elements of a particular artefact" (*pp.42) to be defined and frozen early in the design cycle (Henfridsson et al, 2014) with this only possible if a separation between design and context is created. Alexander (1964) proposed the purpose of design was to find an optimal fit between form (the design created to solve a problem) and the context (the problem) through a process of adaption. However, much of the discourse on design has followed dominant economic thought that views value-in-exchange[1] as a primary. As a result, design has become inherently object orientated where value was 'created' and 'delivered' by the organisation (Kimbell, 2010) and form and function are bound during the design phase (Yoo, 2013).

Together, these definitions show design is part of a linear system of production in which design precedes production and production precedes consumption with the latter not of interest to the organisation (Kimbell, 2011). This conforms to a goods-dominant (G-D) logic rhetoric as described by Lusch & Vargo (2014) in the following figure.

[1] Value in exchange referring to an organisations ability to create, determine and 'add' value during the production process that is then exchanged with the customer, usually for money, and destroyed during the act of consumption by the customer (For a full discussion on value see Ng & Smith, 2012).

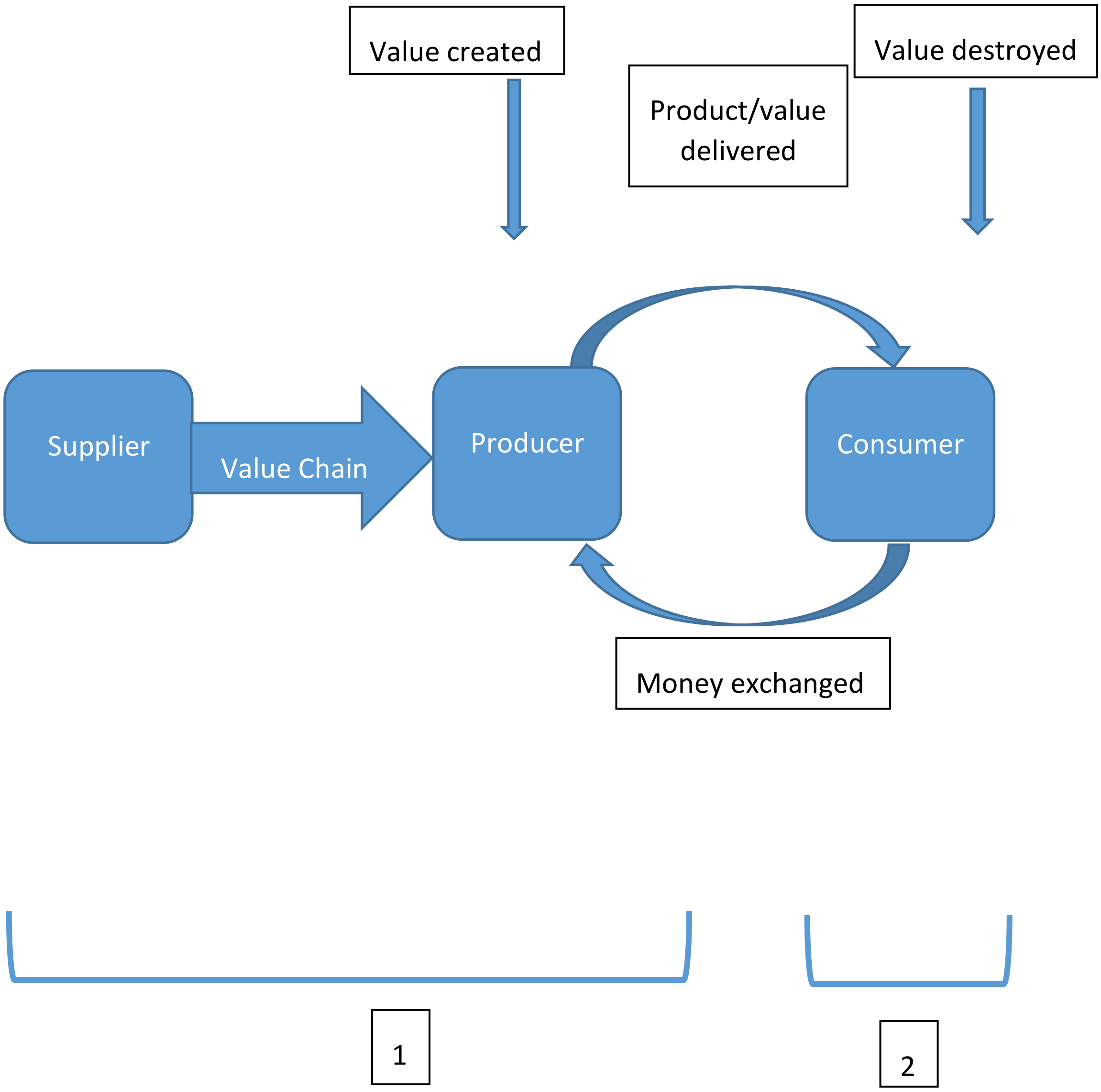

Figure 2.1. Linear view of production focussed on value in exchange (Adapted from Lusch & Vargo, 2014).

Aligning with this process reflects the view that whilst all design focusses on value creation (Ng, 2013), design that specifies a complete artefact prior to exchange emphasises design for low variety. This is discussed in more detail later in the chapter.

Recently, the emergence of customer experience and servitization has brought to the fore the concept of value-in-use, where value is determined by the customer during the use and experience of an organisations value proposition and this has implications for our understanding of design. For example, Voss et al (2008) and Zomerdijk & Voss (2010) discuss the concept 'experience-centric services' that emphasises the context within which the service is experienced. From the perspective of OM, experience is characterised as the use of the product or service. Therefore, the organisation needs to take particular care in the design of both tangible and intangible services (Pullmann & Gross, 2004) and be flexible to individual's needs through careful design of the value propositions interfaces and modules (Avlontis & Hsuan, 2017). In these contexts, OM is concerned with the part of the service concept connected to the how of the service operations concept (Lovelock et al, 1999; Goldstein et al, 2002), where emphasis is placed on converting the service marketing concept (the what) into a deliverable for the customer to use and experience i.e., through service delivery system design (Ponsignon et al, 2015). However, it is important to note that the types of services discussed by these authors are typically traditional service contexts (i.e., healthcare, hospitality, finance) where a face to face interaction between firm and customer is a prerequisite of the service. Here, it is possible for human components of the value proposition to be flexible in use and accommodate heterogeneous needs of the customers. In contrast, within servitization, organisations value propositions are inherently product centric (Baines et al, 2009a), whereby the primary service is 'delivered' via the physical asset and the service activities are designed to support the efficient operation of the asset (Neely, 2008; Baines & Lightfoot, 2013; Vijsnic et al, 2016). In this setting, customers' participate in service away from the organisation, where a face to face interaction is not a prerequisite. The physical asset is often designed as functionally and structurally complete, as in the designing for low variety frame, and once produced, services are coupled to these material assets (Baines et al, 2009a). However, Green et al (2017) question whether existing approaches to design inherited from a goods-dominant (G-D) logic, where the output is a tangible offering and primarily viewed as functionally static (complete), are appropriate in environments characterised by continuous change brought about by the variety associated with individual customers context of use (Ng & Briscoe, 2012; Smith et al, 2014). Garud et al (2008) support this discussion and suggest this is a new frontier scholars and practitioners find themselves in given there is no clear separation between form and context. Instead, they argue that there is only a set of ill-defined problems, fluid preferences and solutions that emerge through the use and experience of the offering where actors assemble and engage with multiple resources (designs) created by organisations in use (Kimbell, 2011). This would suggest that models based upon existing product design processes are not necessarily applicable to service even when the service is product-centric (Ng et al, 2011). This corresponds with existing thought around service design in more traditional service contexts (Shulver & Slack, 1997; Johnston, 1999).

The understanding of design presented in the latter half of the last paragraph is reminiscent of a service-dominant (S-D) logic understanding of resource integration and value creation. For S-D logic, customer's contexts of use are continuously changing and as a result, there is a constant adjustment as to their resource requirements in order to retain a suitable level of system viability (Lusch & Vargo, 2014). With respect to system viability, it can be discussed from the perspective of both the firm and the customer. Thus far, we have aligned with value in context where value is described as a construct attributable to an entity as perceived by another (i.e., the value of what and to whom) (Green et al, 2017). For the rest of this thesis, system viability is defined as a measure of wellbeing of a focal actor's value creating context with the meaning of wellbeing determined by the focal beneficiary themselves. Ng (2013) posits that S-D logic is fundamental in our understanding of value and exchange and states that this has important implications for design. Notably, she posits that designing for contextual experience (i.e., use), organisations need to account for five main components of use within their design activities; institutions, actor agency in context, existing resources in context, the context (system boundaries) and the outcomes of the focal beneficiary in context. In defining these factors, Ng (2013) draws heavily on the S-D logic literature, systems theory and the field of sociology. Institutions aligns with the definition provided by the S-D logic literature, where Vargo & Lusch (2016) define institutions as the '*rules, norms, meanings, symbols, practices and similar aides to collaboration*' whilst institutional arrangement are defined as *'interdependent assemblages of institutions*' (pp.6). Ng (2013) describes institutions as *'norms or patterns' (pp.58)* that can enable or prevent choices and opportunities. Actor agency is defined as *'the capacity of an individual to act independent and to make their own free choices*' (pp.58). In contrast to institutions, agency is the actor's ability to act either within or against the structures that are in place. Both agency and institutions are drawn from the sociology and S-D logic literature. Existing resources in context is defined as the elements (e.g., Ng (2013) provides the example of tea making, where cups, saucers, sunshine, garden furniture, hot water etc. are the resources in contexts) that exist within the value creating context that can be drawn upon by actors in the system to co-create value and achieve the desired outcome of the focal beneficiary. To define the context, Ng (2013) draws on systems theory. She emphasises the need to define exactly what we are looking at and from whose perspective. This understanding of the context is important for defining the systems boundaries. If we do not know what we are looking at, the system has the potential to exponentially grow and increase in complexity. For example, one may want to look just at production in the internal workings of a single factory. However, if one does not define the system from the perspective of the internal production team, the boundary has the potential to extend to the entire supply chain. Second, identifying whose perspective we are looking at the system from plays a role in understanding context, as each individual has different descriptions of the system. Simply, defining the boundaries of the context and identifying whose perspective to view the system from is important for understanding value-creating activities. Finally, the desired outcomes of the focal beneficiary is defined in the context of value creation. For Ng (2013), the outcomes arise from the value we co-create with each of the offerings in context. Here, she describes the co-creation of value in use as non-linear and not transaction based (e.g., value in exchange), but instead, value that is phenomenologically determined in use where interactions between elements of the context are dynamic and kinetic. Thus, Ng's (2013) understanding of outcomes in context aligns with the definition of value in context provided earlier in the chapter.

In identifying these factors influencing an organisations ability to design for use and high variety, she calls on the research community to address designing for high variety from the perspective of modularity theory (Baldwin, 2008) and S-D logic (Lusch & Vargo, 2004; 2008). This fundamentally different approach to design described by Ng (2013) corroborates earlier work by Ng et al (2011) and more recent work by Maglio et al (2015). In their work, they questioned whether simple extensions of existing engineering, supply chain and operations models were applicable within servitized contexts or human-centred service systems. Instead, they asked whether new ways of thinking about design be required where emphasis is placed on value in use, technology, resource integration, emergence and contextual variety. However, it is worth noting the motivation behind the identification of these five factors and the context within which her work is developed. First, Ng (2013) is focussed on new markets in the digital economy. Whilst these factors may be relevant for designing for high variety, and in her book she argues that they are, her work discusses them at a macro, market based level. At this level, they may not provide appropriate direction for the design, creation and delivery of a product and service at a micro level. Second, Ng (2013) is influenced quite heavily by work from sociology and the current direction being taken within the S-D logic literature. Whilst these factors are relevant for the exchange and integration of resources at a 'zoomed out' level (Lusch & Vargo, 2014), criticism of this level of abstraction still exists within the operations and general management fields. For example, O'Shaughnessy and O'Shaughnessy (2009) highlight how S-D logic lacks relevance to practicing managers whilst Sampson et al (2010) highlight that S-D logic provides an interesting descriptive narrative, but lacks any pragmatic and informative theory that is useful for operations management and strategy at the micro level. Based on these discussions, it can be argued that Ng (2013) has provided novel insight into some interesting factors that influence designing for high variety and the modularisation of the customers' contextual experience (use context). However, further work is needed for these factors to provide pragmatic and informative insight into how both the design and operations management functions of an organisation can use these factors to influence their practices at a practical level. That said, what has been discussed highlights important differences between designing for high variety and designing for low variety. First, the boundary that separates design and context as in the designing for low variety frame is removed and they are assumed to have an intimate entanglement when designing for high variety. Second, by extending the boundary and assuming an entanglement between design and context exists, new variables are introduced to the organisations design activities, some of which they do not have control over (e.g., what resources are available in context, actors' agency in context and the desired outcomes).

Recently, Kimbell (2011) brought to the fore different ways about thinking about design and presented these in a two by two framework (see figure 2.2).

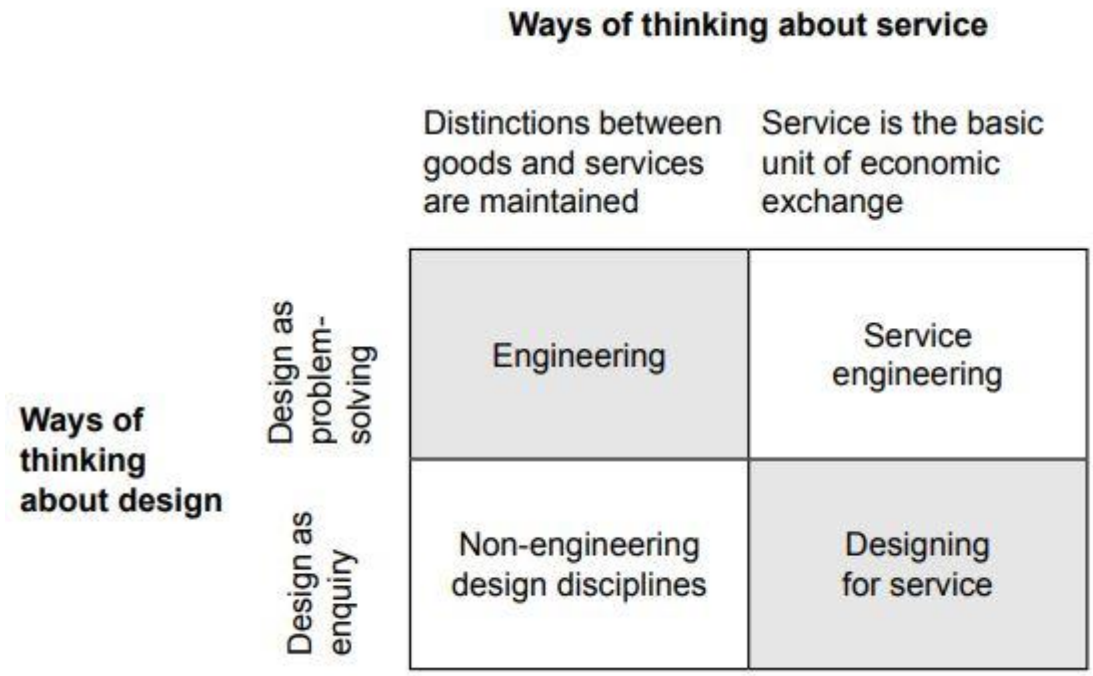

Figure 2.2. Four ways of thinking about design and service (Kimbell, 2011).

The horizontal axis discusses different ways of thinking about service, whilst the vertical axis discusses different ways of thinking about design. For a full review of these categories, the author refers readers to Kimbell (2011). Of particular interest for this study is the top left and bottom right quadrants of the framework. The top left quadrant sees design as a problem-solving activity. Here, the distinction between products and services remains consistent with mainstream management literature whereby services are intangible, heterogeneous, inseparable and perishable (IHIP) and everything a good is not (Nie & Kellog, 1999; Vargo & Lusch, 2004). Furthermore, in this context, design is focussed on systematically designing and creating products and services that can be specified in advance, conforming to the idea of completeness proposed by Garud et al (2008) and the binding of form and function during the design phase proposed by Yoo (2013). That is, engineering design is grounded in reductionism and a scientific approach to design as presented by Simon (1996) where clear boundaries, stable specifications and static outcomes in the outer environment (context) are a primary. Emphasis in this frame is therefore on units of output and low variety in use.

In contrast, the bottom right quadrant conforms to the understanding of service as a process and the application of competencies for the benefit of another or oneself (Vargo & Lusch, 2004). Here, there is no distinction between products and services other than products are a mechanism for the distribution of service (competence) (Lusch & Vargo, 2004). Within the design community, Manzini (2011) argues that designing for service means the designer recognises what is being designed is not the end result, but instead the design is a platform for action amongst a range of different actors over time. The result of this understanding is that it is impossible to fully specify, imagine or plan the design for service since variety may emerge at the point of use and alter the way is which value is co-created by actors engaging in service-for-service exchange (Kimbell, 2011). Thus, the purpose of the organisation is to act as an input into the customers' value creating activities where the organisation designs their offerings around existing customer activities in order to best compliment them (Gronroos & Ravald, 2011). As noted by Ng (2013), this requires the organisation to account for five new variables associated with use and organising their design activities around these new variables may pose a number of challenges to the organisation. However, one common theme and area of great promise for organisations is the ability to leverage digital technology to serve use given the affordances associated with digital materiality (i.e., unbounded materiality) (Yoo, 2013; Holmstrom & Partanen, 2014). A number of scholars highlight that functionally incomplete products[2] and the ability to mobilise resources across different times and space provide a unique opportunity for organisations to focus on value in use. This would allow both the organisation and customer to actively engage in resource integration and (re)configuration at the point of use (Normann, 2001; Garud et al, 2008; Yoo et al, 2010; 2012; Yoo, 2013; Ng, 2013; Henfridsson et al, 2014) even in industries characterised by slow growth and largely material assets (i.e., capital goods) (Maull et al, 2015). Two primary affordances of digital technologies are that it enables the asset to exhibit functionally fluid boundaries because of the unbounded nature of digital materiality (Yoo, 2013; Ng, 2014; Green et al, 2017). This is in contrast to fixed functional boundaries as in the designing for low variety frame. Furthermore, customisation at scale is more affordable than if pursued via traditional manufacturing technology. Within this chapter, the importance of digitisation, digital materiality, the design of the value proposition and the appreciation of customer resources and agency within the designing for high variety frame have been brought to the fore.

Within the previous paragraph, the discussion presented a number of different ways to distinguish between a product and a service, with both the IHIP characteristics and S-D logic understanding discussed. For the purpose of clarity, it is important to clarify what a product and/or a service is within this thesis. Whilst

[2] Incomplete products exhibit fluid functional boundaries that allow the customer to modify or adapt the functionality of a product at any point in time. The primary example used within the literature is the Apple iPhone that are all identical at the point of exchange but unique at the point of use (see Yoo et al, 2010; 2012).

Kimbell's (2011) framework would suggest the definition of products and services within the context of low and high variety strategies would be different, it is important to be consistent across both strategies. This thesis aligns with S-D logic and therefore views service as the application of competence for one's own benefit or another's (Vargo & Lusch, 2004) (see chapter 3 for greater detail). Here, their definition of service transcends both product and services in the traditional sense, to provide an overarching view of service. However, they still distinguish between types of service. For them, a material asset is a vehicle for service distribution and frozen competence (Normann, 2001). A material asset is therefore an indirect service. In contrast, anything involving human interaction is a direct service. They further differentiate these in discussing resources, where material resources are operand and intangible resources (knowledge and skills) are operant. Service occurs when operant resources act upon other operant resources or an operand resource. This definition provides consistency in the definition of service for the remainder of this thesis and allows the two different design approaches to be studied with a consistent definition. In particular, this thesis pays particular attention to the design of indirect service and how organisations apply their competency, view the competencies of the customer and their role within the service system to provide different degrees or types of service with respect to the physical asset.

Thus far, some simple characteristics of both approaches to design have been presented. Designing for low variety emphasises value-in-exchange, the systematic design of a complete, functionally static offering and the customer as exogenous to the system. In this instance, design is informed by a single snapshot of use which is frozen in the form of a functional specification. In contrast, designing for high variety emphasises value-in-context, a functionally incomplete offering and the customer and their context as endogenous to the system. Thus, design is a continuous process of resource (re)adjustment based on the desired outcomes of the actor in use. Whilst these are fairly abstract distinctions, it provides a suitable basis for comparison with respect to when one design strategy may be more suitable than another. For instance, in contexts characterised by fairly predictable and repeatable activities and desired outcomes, a designing for low variety strategy may be more appropriate. In contrast, in contexts characterised by less predictable and more dynamic contexts of use, a designing for high variety approach may be more suitable.

The discussion thus far has presented two distinct approaches to design. That of designing for low variety and that of designing for high variety. These are now discussed in greater detail.

2.2.1 Designing for low variety

Designing for low variety fundamentally conforms with the top left quadrant of Kimbell's (2011) framework, whereby organisations focus on the systematic creation of complete, value-laden artefacts and/or services that are exchanged or delivered by an organisation (Garud et al, 2008; Kimbell, 2011; Green et al, 2017). In line with OM, the unit of analysis from this perspective of design would either be the organisations products or processes or the manufacturing business unit (Hayes, 2002; 2008), where the design of a product or service can be specified in advance of its exchange and/or delivery (Baldwin & Clark, 2000; Garud et al, 2008; Yoo, 2013).

In conforming to the top left quadrant of Kimbell's (2011) framework, designing for low variety is characterised by what Garud et al (2008) call a scientific approach to design, where emphasis is placed on completeness and a separation between form and context, thus emphasising value in exchange. The use of the term low variety reflects the separation of form and context, as this allows organisations to assume a fixed use (low variety) of the offering once it has been designed and exchanged. Based on this understanding of designing for low variety, it is possible to visually depict the approach in the following figure.

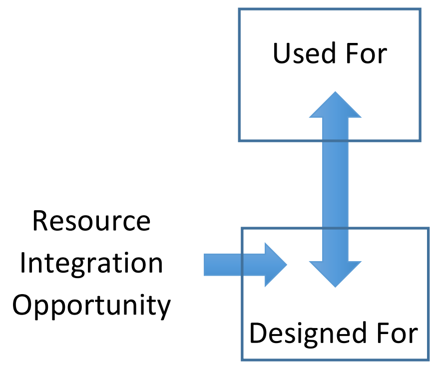

Figure 2.3. Illustration of designing for low variety.

As shown within figure 2.3, use (context) and design are separate, with organisations focussing on the integration of resources within their design and production activities in order to propose and exchange a 'complete' offering in the market. Whilst firms claim to accommodate different customer requirements through product variety (Pine, 1993; Salvador et al, 2002; Salvador, 2007; Patel & Jayaram, 2014), it is created within the mind-set of value in exchange. Therefore, products developed within these strategies are still fundamentally a pre-packaged bundle of functionality serving as a stable platform for service delivery once it has been exchanged with the customer (Spring & Araujo, 2017). Thus, it is functionally static during use and unable to accommodate high variety should the users use the offering outside of contexts it was initially designed for. With respect to variety, OM has traditionally treated variety as a disturbance introduced by the customer and that they should separate design and context to minimise the disturbance and maximise efficiency of the technical core (Godsiff, 2010). The primary way to remove variety from the organisations technical core was to reduce the number of customer contact points from the organisations operations as much as possible (Chase, 1978; Kansan & Proenca, 2010). This approach to the minimisation of variety resulted in a closed system of production where the customer was exogenous to the organisation's design and production activities. This aligns with the design for low variety frame where design and context are separated. Within a service context, it was found to be more difficult to remove customer induced variety from the production system and that the presence of the customer meant the technical core had been breached (Frei, 2006; Godsiff, 2010). In this instance, for an organisation to continue to viably serve the customer, it was important they matched the variety associated with significant customer inputs (Frei, 2006).

The concept of designing for low variety as described above can be illustrated using the modularity literature and the design of physical offerings.

2.2.1.1 Modularity for low variety

Modularity emerged in the 1960s as a method for managing a complex system efficiently (Simon, 1962; Baldwin and Clark, 2000). In this instance, complex is deemed to reflect non-simple interactions amongst interdependent parts of a system (Simon, 1996). A modular system is able to manage the complexity via a process of information hiding (Parnas, 1972). Here, the complex, non-simple interactions and the principle design decisions of that module are hidden behind a module boundary. At the boundary of a module, the designers define a standardised interface that allows the module to be loosely coupled to the rest of the system, but remain tightly coupled (complex) within (Baldwin & Clark, 2000). Based upon these principles, modularity is seen as a general systems concept and can be described as *'the degree to which a system's components can be separated and re-combined, and it refers both to the tightness of coupling between components and the degree to which the "rules" of the system architecture enable (or prohibit) the mixing and matching of components'* (Schilling, 2000 p.312). der Laan et al (2016) suggest modularity follows a three step decomposition logic as deduced from studies by Simon (1962) and Alexander (1964). These include identifying system boundaries, identifying the subsystem and finally, analysing the interdependencies between the modules of the system. The primary purpose of decomposition is therefore to increase component independence through the creation of standardised interfaces that are designed to alleviate tensions between modules within the system (Sanchez, 1995). Decomposition can occur in two ways; structurally and functionally. Structural decomposition is usually a hierarchical relationship between components that represent a similar kind of thing (e.g., physical, electrical, etc.) and represent whole part relationships (Kusiak & Larson, 1995). Examples of structural decomposition include product breakdown structures and bill of materials. In contrast, functional decomposition refers to the direct mapping of function to physical components of a given subsystem or module. Ulrich (1995) provides an example of this where he maps functions of a trailer onto each module of the trailer. From a modular architecture perspective, the mapping would be one-to-one between function and physical component. The main differentiating factor between the two is that functional decomposition, commonly associated with product modularity (Kusiak & Larson, 2013), benefits from the independence of components that allows the organisation to benefit from standardisation and interchangeability. According to Kusiak & Larson (1995), functional decomposition takes advantage of the lack of dependency between the physical components within the products architecture and this is reflected in a numerous articles (e.g., Ulrich, 1995; Baldwin & Clark, 1997). In contrast, because structural decomposition captures relationships in a hierarchical model, it relies upon the dependencies between subsystems, modules and components in a manner that functional decomposition does not. Within modularity theory, functional decomposition is the most common and throughout this thesis, unless stated, decomposition will be used to refer to functional decomposition.

At the heart of modularity theory is the module, which has commonly been described as a physically distinct portion of a product that delivers a pre-specified function (Ulrich and Seering, 1988; Ulrich, 1995) and as being tightly coupled within but loosely coupled to the rest of the system (Baldwin and Clark, 1997). The notion of tightly coupled within and loosely coupled to the rest of the system is a concept derived from the computer science field where Parnas (1972) coined the term ‘information hiding’. Information hiding is a process of hiding elements or design decisions that are most likely to change behind a boundary (interface). As in modularity theory, this allows for the autonomous evolution of modules without affecting the rest of the system as the change takes place (Baldwin & Clark, 2000; Pil & Cohen, 2006). Organisations are therefore able to innovate at both the modular level and the architectural level, but not necessarily both at the same time (Henderson & Clark, 1990).

This theory has primarily been developed within the context of product and service design. For example, dominant frameworks within modularity theory can be traced back to Baldwin and Clark (1997) who, focussing on physical products, present three core components nested within the broader concept of design rules (i.e., the visible information that allocates functions to modules and the creates and defines interfaces between said modules):

- The architecture – this specifies what modules are to be included within a system and what function is allocated to said modules;
- Interfaces – these specify how the modules defined in the architecture will interact with emphasis placed on how they will fit together and transfer energy, material and information; and

- Standards – these test whether a module conforms to the design rules with respect to both its functionality within the system and its performance in comparison to another module (Baldwin & Clark, 1997).

As noted in section 2.1, Baldwin & Clark (2000) specify that designers require a complete picture of the structural elements of the product so that these can be frozen into the product architecture prior to release to the production team (Henfridsson et al, 2014). The term frozen refers to the point at which design decisions, with respect to functionality, are difficult to change. The idea of design freezing (i.e., fixing the design specification) is important for organisations who wish to achieve scale economies in production. Design changes are more difficult and expensive to achieve once the specification has been transferred to production for the conceptual design to be converted into an actual offering (Henfridsson et al, 2014). Thus, there are limited windows for redesign post release of the frozen design specification to the production team and the functionality that is transferred at this point, remains fixed (frozen) through life. Thus, 'freezing' specifies that clear boundaries, fixed specification and stable outcomes in use are a prerequisite of modularity for low variety and supports Garud et al (2008) who claim design for completeness mandates a separation between design and context. However, it is noted that digital technology allows this point of freezing to be extended beyond design, improving design flexibility through life (Henfridsson et al, 2014). This suggests some of the limitations of design flexibility are a result of limitations in the technology used to create and deliver the product or service. This is further addressed in section 2.4. This separation of design and context is captured by

Langlois and Cosgel (1998) who, referring to propositions by Pareto, have said *'we do not need the consumer to be present at all so long as he leaves us a snapshot of his preferences'* (p.107). Creating this snapshot allows organisations to freeze the user requirements so that they can inform a complete description of the structural and functional elements of the product architecture in advance of production. The importance of specifying the complete description of the architecture during the design phase not only allows a separation between design and context, but also allows organisations to separate their design and production activities. Separating these two activities allows organisations to create flexibility in design (Ulrich, 1995; MacCormack et al, 2001), economies of scale during the production phase as unit costs can be decreased through standardisation and component commonality (Salvador, 2007) and the opportunity to leverage external organisations manufacturing capabilities within the supply chain (Fixson, 2005; Langlois, 2006). Within service modularity, the same logic is visible. Within a study for the daily living of elderly patients, de Blok et al (2010) found there was an inversion of product modularity as described by Duray et al (2000) for service modularity but designs are still specified in advance of use. This is illustrated in the following figure where Duray et al (2000) typology is presented on the top with de Blok et al (2010) on the bottom.

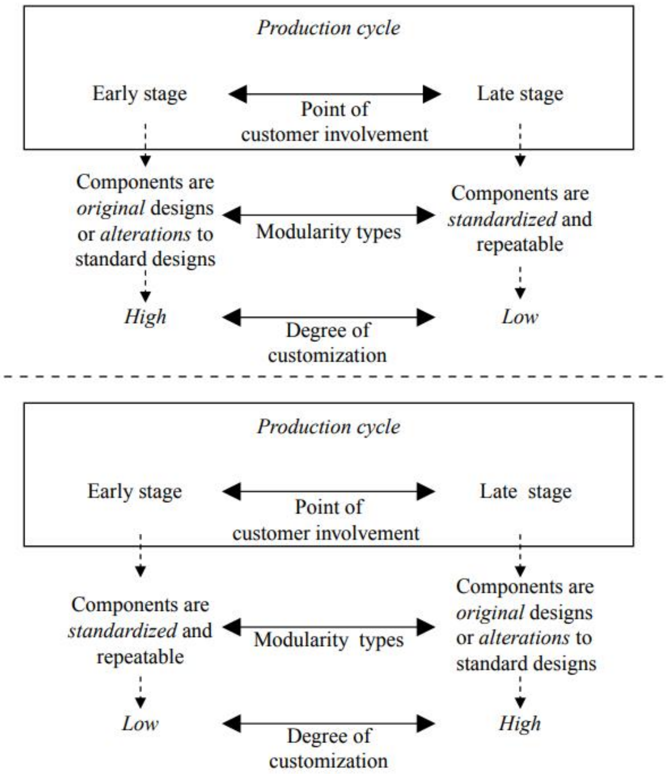

Figure 2.4. Manufacturing modularity vs. service modularity: an inversion (source: de Blok et al, 2010).

It is important to note that late stage does not mean the daily living of the elderly patients and their use of the service package, but instead the specification of the service package once intervention from healthcare professionals is required. This is reflected in the fact that their unit of analysis is the specification of the service package. Late, in this case, refers to a house visit from the healthcare professional to discuss with the patient their needs and understand their living arrangements and from there, how the organisation can tailor the service package to best accommodate their needs. Thus resulting in 'late' customisation. This highlights how service modularity conforms with Garud et al (2008), Kimbell (2011) and existing modularity theory in that complete designs are specified in advance of their use and once produced, little room for functional design change is left.

Given modularity theory within the context of service, engineering and product design specifies the architecture needs to be defined early on, it leaves very little room for changes to either the architecture or the final form produced by the organisation once the design has moved from the design team to the production team (Iansiti, 1995; Verganti & Buganza, 2005; Buganza & Verganti, 2006; Henfridsson et al, 2014). In emphasising completeness and value in exchange, the organisation limits the window within which alternate design options can be pursued should the context for which they are designing for changes post production of the original offering (Henfridsson et al, 2014). This is seen as a characteristic of modular architectures that seek to contain complexity (non-simple interactions between modules within the architecture that emerge through the integration of new modules and functionality) through the complete specification of the design, via a process of function binding (i.e., the function has been bound to a particular form), prior to production and use (Yoo, 2013). In emphasising a complete specification of functional and structural elements, the organisation assumes a low variety of use. Thus supporting Garud et al (2008) and Green et al (2017) who suggest strategies focussed on exchange may not be suitable for contexts characterised by continuous change and high variety in use. With respect to flexibility toward change, MacCormack et al (2001) have studied flexibility in design to accommodate emergent needs of customers or technological change, but the architecture and structural components of the design are still frozen prior to the release of the design to the production team. Thus, if anything emerges post design, organisations have not developed suitable strategies to be able to cope with change through life. In line with this discussion, Verganti & Buganza (2005) suggest strategies for through life flexibility, where changes can occur efficiently post release to the market, are needed. Following the discussion of modularity for low variety, a general understanding of modularity for low variety is presented in the following figure.

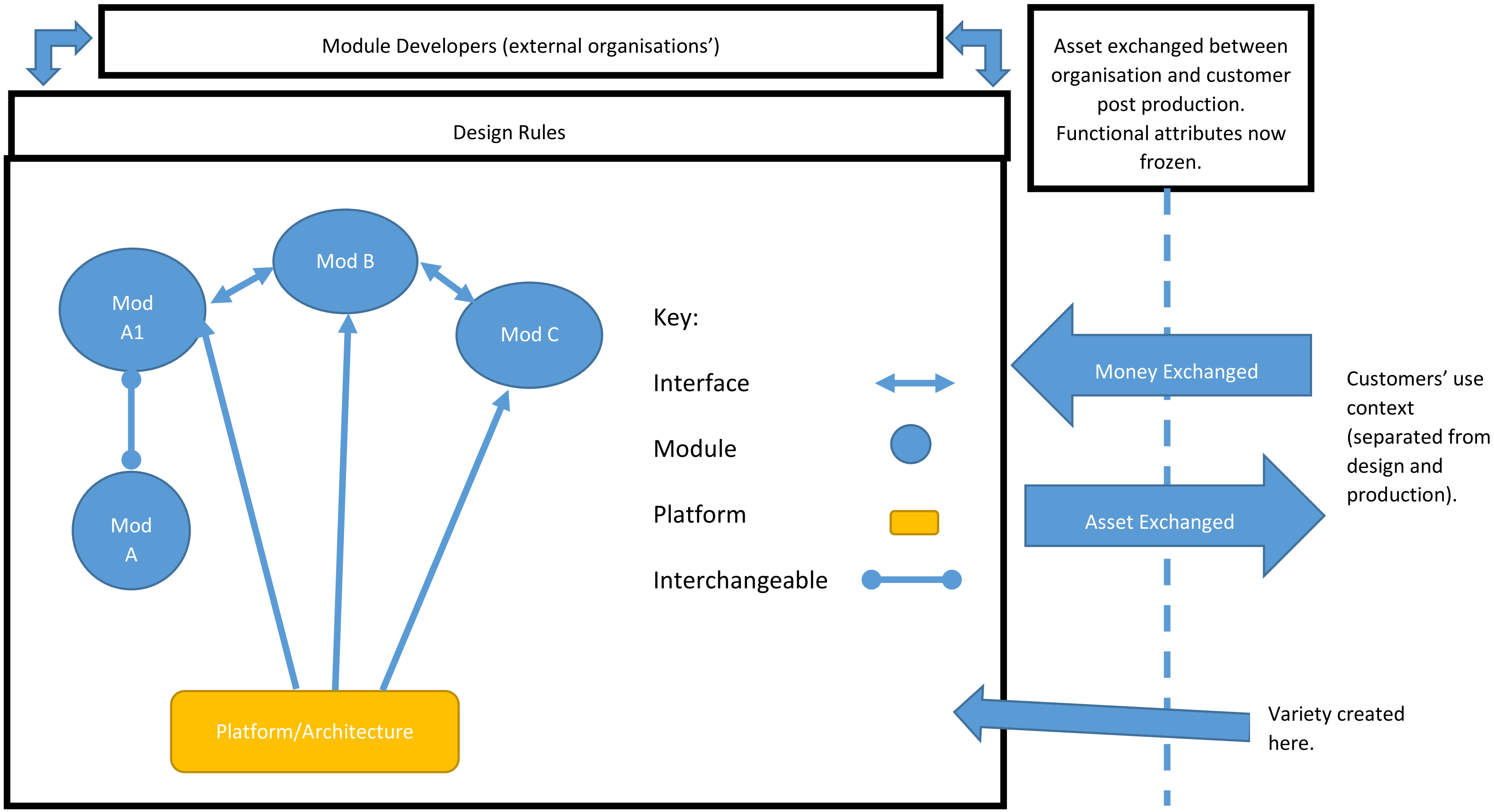

Figure 2.5. Generic understanding of modularity for low variety.

Figure 2.5 illustrates that organisations create an architecture that specifies functionality of the modules and the interfaces between them prior to exchange with the customer. Through the creation of design rules, the organisation can choose to leverage the manufacturing and design capabilities of the supply chain who can create modules (i.e., within the context of computers, peripheral devices such as printers, mice, keyboards etc.) at a lower cost due to their knowledge and expertise in these areas. Product variety is created within the boundary of the organisation, as specified by the black line, and is presented to the customer as a stable platform for service delivery at the point of exchange. The dotted line represents the exchange, usually monetary, and the separation between form and context. Based on the review, a number of foundational components of modularity theory as presently understood from the perspective of designing for low variety have been identified and are presented in the following table.

Attribute	**Definition**
Modularity	Modularity is a strategy for organisation of complex products and process efficiently and is the use of standardized and interchangeable parts or components to enable product variety (Baldwin and Clark, 2000; Jacobs et al, 2007). More specifically, modularity refers to

	the ability for an organisation to describe the architecture (structure), the functionality of components (modules) and the relationships between them (interfaces) so that the system can be replicated, components replaced and the system managed efficiently (Bask et al, 2010). Modularity specifies a complete description of structural and functional elements prior to transferring the design to the production team.
Module	Tightly coupled within but loosely coupled to the rest of the system (Baldwin and Clark, 2000).
Design Rules	Design rules define how an artefact works, what it does, how it does it and how it is to be manufactured. Design rules form part of the architecture, allocating functions to modules and define the interfaces between modules

	of the system (Brusoni & Prencipe, 2006). Design rules can be made up of specific operating principles or strategic and organisational components, such as mass customisation.
Interfaces	Interfaces are the boundaries of the modules facing each other and allow other module developers to ensure interoperability between modules (Baldwin & Clark, 2000).
Interaction	Interactions describe the input and output relationship between modules and need to be compatible. Interactions are a precondition for the existence of an interface (Miller and Elgard, 1998).

Table 2.1. Core concepts and definitions of modularity for low variety.

Following the discussions presented thus far, designing for low variety is defined as:

"A design strategy, underpinned by a scientific approach to design and reductionism, that emphasises the separation of design and context and the complete specification of the design prior to exchange"

Following the principles of modularity as discussed here, it can be argued that organisations may struggle to contain complexity, with respect to containing non-simple interactions inside of defined modules, if design changes are implemented post production. This is because the integration of post-production design changes that satisfy through life changes (i.e., of customer needs or technology changes that require new functionality) does not conform to the principles of modularity theory that specify the need for function to be defined early on in the design cycle, prior to production. Simply, interfaces and design rules for new functionality (i.e., not part of the original specification) post production do not exist and this has implications for the organisation with respect to the management of design complexity (managing the non-simple interactions within the product's architecture). This would seemingly contradict the existing modularity literature, where it is argued it is a suitable strategy for managing architectural complexity (Ethiraj & Levithal, 2004) and that modules can autonomously evolve without increasing the complexity of the rest of the system (Pil & Cohen, 2006). This thesis contends that existing modularity studies, focussed on exchange and low variety, do not consider post production design changes that introduce new functionality within their unit of analysis. Instead they focussed on the integration of upgrades that consisted of the same functionality with improved performance (Ulrich, 1995) and thus constituted a modular innovation that did not change the interfaces or interactions amongst components within the system (Henderson & Clark, 1990). Focussing on upgrades allowed complexity (non-simple interactions and the design decisions of a module) to be contained as the structural and functional elements had been pre-specified during the design stage. However, whilst the literature is converging on the idea that modularity for low variety is not suitable for use contexts, it is apparent a lack of empirical work exists within this area and no work has been conducted to within this area.

2.2.2 Designing for high variety

In contrast, designing for high variety emphasises the customers' context and the continuous process of resource integration for the continual modification and (re)configuration of resources in use to support the co-creation of value. In particular, it pays tribute to the fact that value is contextual and determined by actors during their interaction, use and experience of the organisations offering in conjunction with resources provided by other members of the value constellation (Kimbell, 2010; Ng, 2013). Understanding value as contextual highlights that value creation is dependent not only on an actors ability to integrate and exchange resources, but the context within which they reside (Chandler and Vargo, 2011; Ng and Smith, 2012). Thus, each instance of value co-creation is uniquely and phenomenologically determined by actors during the process of resource integration and use (Chandler and Vargo, 2011). Value is therefore intrinsic to the system and its design is determined by the adaptive actions of actors who engage in service-for-service exchange and occupy roles within the service ecosystem (Lusch, et al, 2010). This suggests that determining value can only be understood when placed within the context of the system it emerges from (Edvardsson et al, 2011). From this review, the relationship between understanding value and resource integration from a S-D logic perspective and the concept of incomplete design as discussed by Garud et al (2008), Manzini (2011) and Kimbell (2011), is evident.

Furthermore, in appreciating that design cannot be fully specified in advance suggests context is characterised by continuous change and leads this literature review to conclude that an incomplete approach to design as outlined by Garud et al (2008) would be a suitable strategy to follow when designing for high variety.

For designing for high variety, the primary unit of analysis is the customers' consumption space where the organisation is an input into their value creating activities (Gronroos & Ravald, 2011; Green et al, 2017) and variety is considered to be a emergent property of use that the organisation must manage and design for if they are to satisfy the desired outcomes of the focal beneficiary (Batista et al, 2012). Therefore, a primary property of designing for high variety is being able to mobilise resources for the customer to integrate into their context of use for the purpose of absorbing variety, maximising resource density and co-creating value (Normann, 2001; Michel et al, 2008a; Lusch & Nambisan, 2015). Density refers to the most appropriate combination of resources mobilised for an actor at any given time and place to support the optimal co-creation of value (Lusch & Vargo, 2014). Therefore, design has a lot to do with whether the individual can access resources to achieve their outcomes in use (Ng, 2013) with a number of propositions put forward thus far suggesting digitisation could support this. In adopting this unit of analysis, designing for high variety aligns with what Payne et al (2008) call an outside-in approach to design. Exemplars of this understanding can be found within the servization literature (Ng & Nurudupati, 2010; Smith et al, 2014; Green et al, 2017; Spring & Araujo, 2017) and are discussed in chapter 4.

Designing for high variety is therefore characterised by incompleteness and the understanding that design and context are intimately intertwined and serving use is a constant process of resource readjustment. This is illustrated in the following figure.

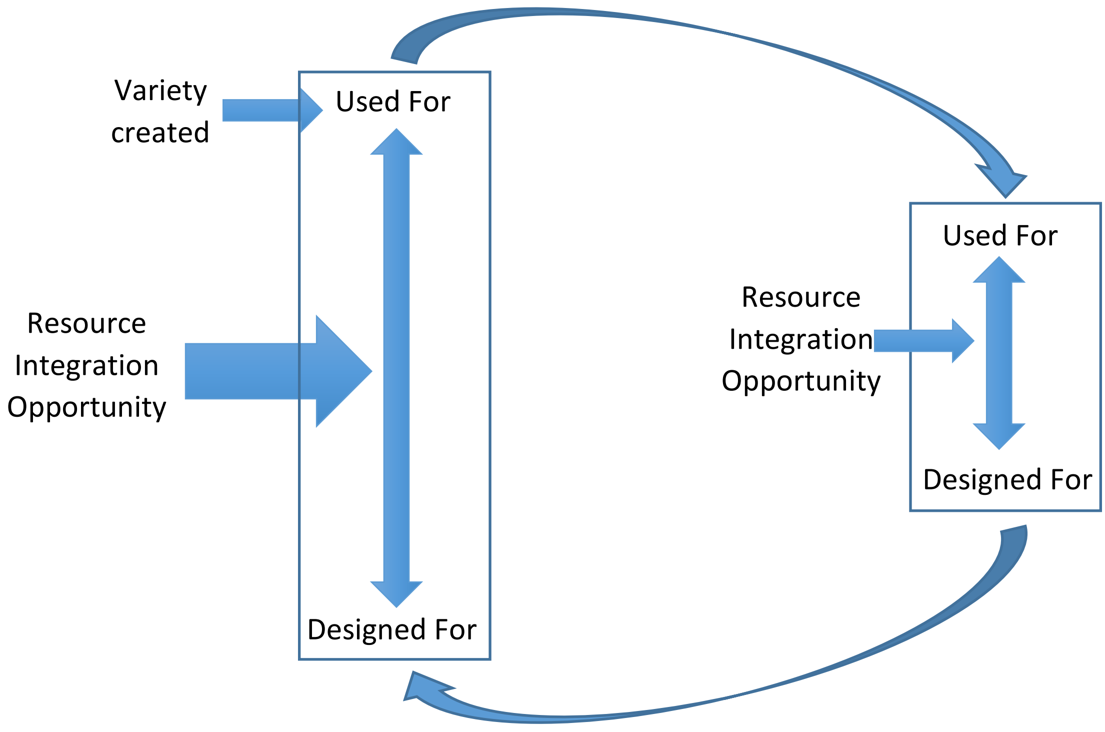

Figure 2.6. Illustration of designing for high variety.

Within figure 2.6, what the design was intended for and what it is used for are contained within a single box to show how they are entangled. On the left-hand side of the illustration, the large arrow between used for and designed for depicts a gap between the problem (context) and the design created by the organisation. This represents a level of disparity between form (the resources/design) and context and thus restricts an actor's ability to co-create value. The purpose of the organisation is then to act as an input into the customers' context of use to try and resolve this disparity through the proposal of new or existing resources that can be integrated by the focal beneficiary. The customer then uses their agency and operant resources to integrate resources from either the organisation or another organisation within the service ecosystem to provide a better fit between form and context. Thus, design is an adaptive process of resource integration as determined by the focal beneficiary and the organisation needs to organise themselves to mobilise their resources around these actors. Once integrated, the fit between form and context is optimised, at least temporarily, as the resources fit with the outcome the customer wishes to achieve in use. This is represented by the right-hand side of the figure, where the resource integration opportunity shrinks and the gap between used for and designed for is minimal. Given variety emerges in use, this process of design and resource integration is continuous as the customers' ability to co-create value is continually changing. With respect to variety, designing for high variety views variety as emerging in context (Green et al, 2017). Thus, in contrast to existing thinking where the customer breaches the organisations core, for designing for high variety the organisation breaches the customer's core and in order to satisfy emergent needs at the point of use, the organisation must match the variety of use through the provision of heterogeneous resources for value creation.

The following section discusses three examples of designing for high variety from the extant literature.

2.2.2.1 Examples of designing for high variety

The first example comes from Schilling & Paparone (2005) who apply the general modular systems theory developed by Schilling (2000) to military force development. In her original article, Schilling (2000), drawing on organisational modularity, developed a causal model that explained why systems migrate toward or away from an increasingly modular form. This framework is presented in the following figure.

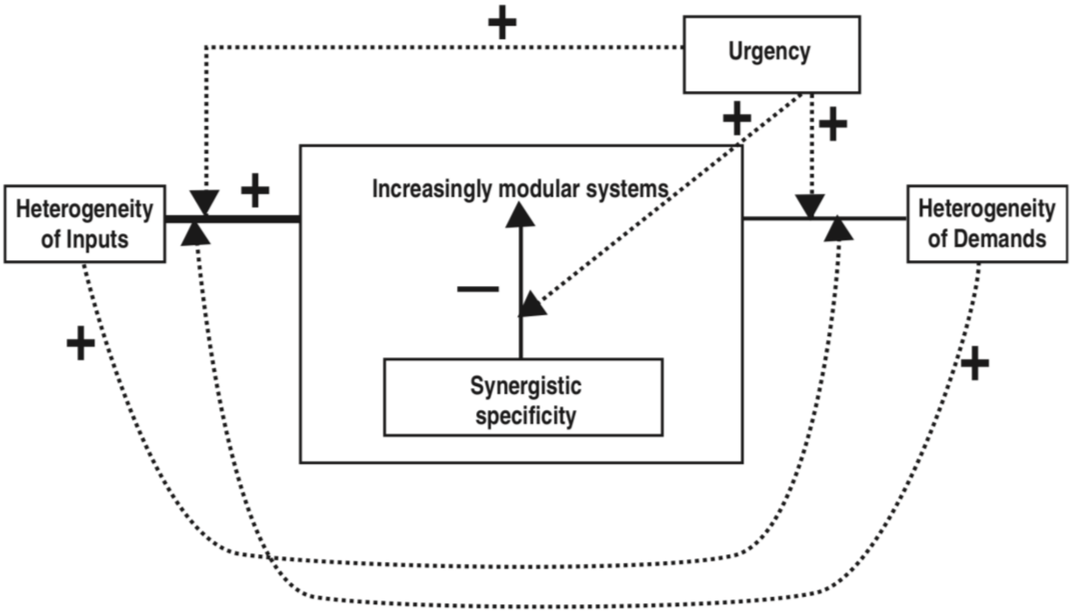

Figure 2.7. Framework for a general modular systems theory (Source: Schilling, 2000).

Figure 2.7 shows that systems become increasingly modular when the heterogeneity of inputs and heterogeneity of demand are high, with both providing reinforcement effects for one another. Furthermore, urgency of technological advances and competition push a system toward an increasingly modular state indirectly through the reinforcement of the three primary constructs of the model. The idea of urgency here refers to speed of change, with a modular system encouraging speed of change as modules can be mixed and matched efficiently (Schilling, 2000). However, it is important to note that whilst it affords urgency of change, the changes that can occur at speed are those already defined within the system (i.e., the systems designer has included the required functionality in the specification before the change is required). Therefore, urgency of change, even in a modular system, is restricted by the design decisions made prior to production. In

Schilling & Paparones (2005) study, they applied this framework to the context of US force development to understand why military task forces might shift toward greater levels of modularity, with the benefit of migrating towards modularity being that they can be rapidly configured to address tasks on a mission by mission basis. Thus, whilst the model they developed does not inform how to design for high variety, it does provide insight into why modular or integral systems are more beneficial for certain use contexts i.e., when a greater level of configurability afforded by modularity is needed or greater functionality and performance afforded by integrality is needed (Ulrich, 1995). In the application of the model, they found a number of reasons why a military task force would migrate toward and away from an increasingly modular state. These are presented in figure 2.8.

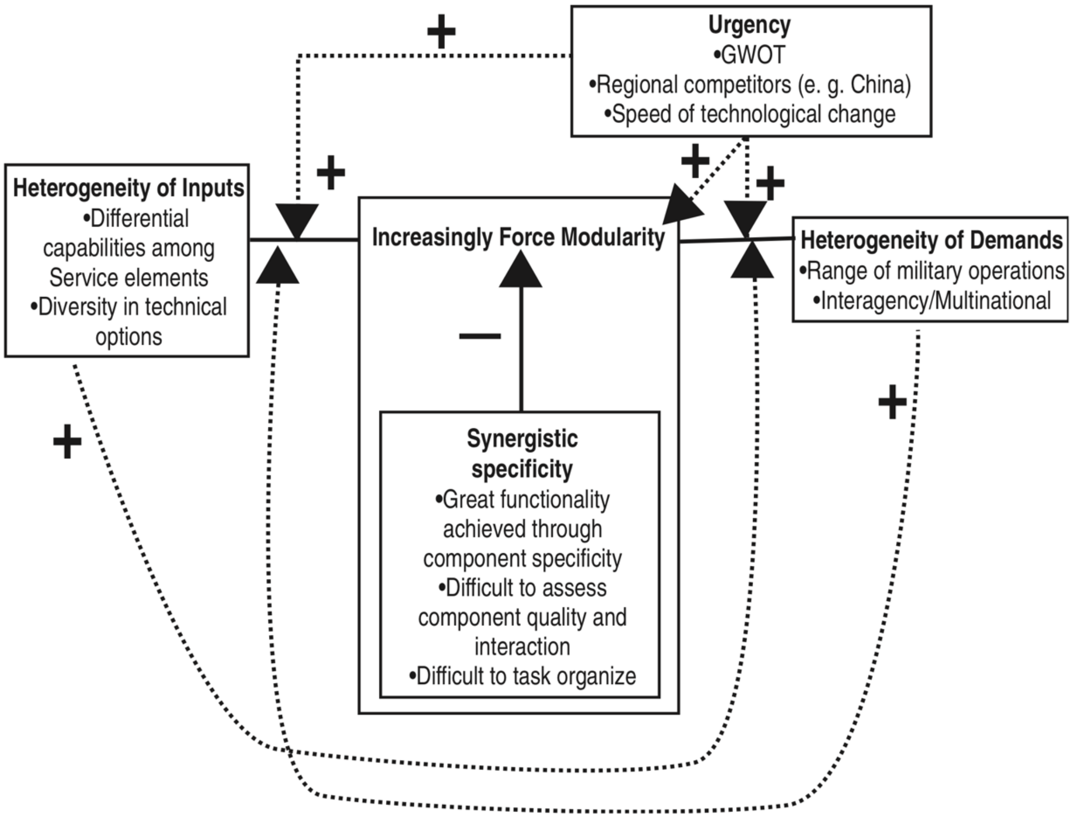

Figure 2.8. Factors influencing the level of modularity in a system (source: Schilling & Paparone, 2005).

The primary benefit surrounding the framework and associated illustration in military force development is that it provides organisations with a causal model that can help them predict and explain a systems migration toward a modular or integral state and why each type of system may be better suited to different acts of value co-creation. In being able to plan and predict these conditions gives the organisation the ability to plan the design of their forces with greater confidence that the configuration is suitable for the context within which they will be operating. However, whilst beneficial to the focal beneficiary in use, their framework does not provide great insight into how an organisation can design for high variety and a number of the characteristics associated with use that have been identified throughout this review are not evident (e.g., agency, institutions etc.)

within Schillings (2000) framework. However, it is important to recognise the contribution of the authors in one of the first attempts at generating a causal model that explains why systems migrate toward or away from modularity. Notably, the authors also conclude by stating that whilst their model may not provide all the answers and future scrutiny may find notable weaknesses in its assumptions, if it provides the foundation for a more comprehensive model, then their work has served a useful purpose.

The second example, Holmstrom and Partanen (2014) focussed on 3D printing technology and servitization enabled digital transformation. Within their study, they emphasise how the combination of digital manufacturing methods[3] and equipment-in-use (i.e., during the customers' experience of the offering) can lead to transformation via servitization and infrastructural evolution. Namely, when a product is deployed alongside digital manufacturing technologies, there is the potential for the equipment to be tailored to use. This can be done through the novel combination of 3D printing, use information collected by users and the infrastructure that allows digital models to be available for the customer at the point of use. In a separate study on 3D printing, Ihl and Piller (2016) also show how the close proximity to the customer allows access to 'sticky' customer information to be utilised for the manufacture of components via 3D printing so that they are better suited to individual customer requirements.

[3] Digital manufacturing methods refers to manufacturing techniques, such as 3D printing, that produce parts directly from a digital file without the need for tooling or mould set up (Holmstrom et al, 2016).

By focussing on a digitally driven servitization transformation, the authors point out that OEMs could overlap product design and improving equipment in use to allow the organisation to move from designing product types (i.e., product families designed for low variety) to product instances (i.e., designed for high variety), where the focus is on the customers' use of the asset and resource (re)configuration. They labelled this type of transformation as a form of product Darwinism where the physical assets configuration is continually assessed based on the customers ever-changing contextual requirements. In this instance, it is interesting to note that information is a primary and it is the information of the use context, the customers' outcomes and their available resources that drive new combinations of the asset. This means the physical world is a derivative of the information and available resources in use with the unique affordance of digital materiality allowing the binding of form and function to be almost permanently delayed. This means digital materiality allows for the product or service is temporarily complete when a particular configuration of resources is required for outcomes in use (Yoo & Euchner, 2015). The concepts proposed within this study fundamentally conform to the illustration of designing for high variety contained within figure 2.4. Notably, the ability to focus on product instances where assets can be adapted, modified and altered on a mission by mission basis is increasingly relevant and popular within practice. This is evident from both the example in chapter 1 from the DoD and the fact that the concept was subject to a recent call for ideas from the Centre of Defence Enterprise (CDE)[4], a department within the UK Ministry of Defence (MoD).

In the third example of designing for high variety, Parry et al (2016) focus on reverse supply chains and the operationalisation of the Internet of Things (IoT) for the development of four use visibility measures. Their study employed an exploratory case study research design to explore how the IoT can improve the accuracy and timeliness of use information to improve and inform reverse supply chain decision making. Within their study, they model use processes of individuals in their consumption space, using an IDEF-0 methodology illustrated with IoT and qualitative data, to generate an insight into their value creating activities over time. Their study proposes four use visibility measures: experience, consumption, interaction and depletion. Taken together, the four use visibility measures allow the organisation to generate an understanding as to the individuals use context through visibility of their homes. This includes interactions amongst different household resources and not just those resources created by the organisation. The implications of their study allows organisations operating reverse supply chains to better understand the process of use and the ways in which their offerings are used by individuals. By focussing on individual use processes, the authors emphasise the variety associated with different contexts of use and how reverse supply chains can be designed around these high variety contexts. This has implications for understanding and designing for different individuals patterns of use. In particular,

[4] For more information about the call for ideas please see https://www.gov.uk/government/publications/cde-themed-competition-additive-manufacturing

the authors note that establishing an understanding as to the types of patterns of use of their offerings will create much richer data sets and as a result, could result in reduced uncertainty during sorting and diagnostic processes for reserve supply chain operators. Beyond the context of their study, it is possible to see the broader implications of their findings for designing for high variety. In understanding patterns of use and interactions between the organisations offering and other resources in context, it will present the organisation an opportunity to observe how their offerings are being used as platforms for engagement and value creation and how the organisation is best placed to compliment these value-creating activities over time.

In sum, the latter two studies addressed designing for high variety within different contexts and were enabled by different digital technologies. Two common themes were shared by both studies. First is that designing for high variety is process orientated and integration of resources in use forms a part of that process. Second is that both studies highlight the important role technology plays in designing for high variety and focussing on value in context. This aligns with propositions by Neely (2008) Ng & Wakenshaw (2017). First, Neely (2008) states digitization will not only support existing value propositions, but also enable new types to emerge. Second, Ng & Wakenshaw (2017) who posit that IoT would allow non-linear business models to emerge, enabling organisations to create thin crossing points (Baldwin, 2008) at the point of use where resources can be integrated efficiently and effectively to satisfy latent needs of individuals in use.

2.3 Contributions to understand designing for high variety as a process of resource integration

From this literature review of design there emerge several contributions to understanding designing for high variety as a process of resource integration. Perhaps the clearest examples are provided by Garud et al (2008), Kimbell (2011) and Ng (2013). Garud et al (2008) discusses design from two perspectives, that of completeness and that of incompleteness. The authors argue that completeness means the design is systematically created so that when it is offered to the market it is functionally complete. This means it exhibits static functional boundaries that cannot accommodate variety in use (Ng & Briscoe, 2012). Thus, they are designed to accommodate contexts that exhibit low variety. Furthermore, a defining characteristic of designing for completeness (low variety) is a separation between design and context. In contrast, designing for incompleteness (high variety) is the opposite. It assumes environments are characterised by continuous change and that the process of design therefore mandates that design and context are intimately entangled, specifying a level of incompleteness in the offering that can adjust to changing use requirements over time. A particularly interesting point made by the authors is that the process of discovering new designs may only take place through the process of participation with the actors in use and the unfolding of this process leads to changes in the problem for which the organisation then has to satisfy. Kimbell (2011) drew upon S-D logic and its understanding that everything is a service. In aligning with this logic, the authors recognise that design is an enquiry over time and requires a different approach to design than those who specify completeness at the point of exchange. Instead, Kimbell (2011) recognises value is underpinned by value in use and this has implications for both the understanding and process of design. The outcome of her discussion is that the purpose of designing for service may mean it is not possible to plan, specify and execute a number of designs in advance, given problems may unfold overtime as actors engage in resource integration. Finally, Ng (2013) proposed designing for high variety required consideration of five things; institutions, the context, agency of actors in use, resources in context and the desired outcomes of said actors. Taken together, Ng (2013) proposed that these five attributes form a foundation for designing for high variety, where emphasis is placed on designing for constant adjustment of resources through the process of resource integration across different times and space. Importantly, Ng (2013) paid attention to the theoretical underpinnings by suggesting modularity theory as described by Baldwin (2008) was particularly relevant to designing for high variety.

2.4 Technology as an enabler for designing for high variety

Throughout the review of the literature thus far, the literature has shown technology to be an enabler in allowing organisations to design for high variety. Whilst much of the literature has focussed on implementation of the technology in organisations manufacturing business units (e.g., Mellor et al, 2015), Dinges et al (2015) recently presented 3D printing as a technology of the future for servitized business models and it is this technology that is of particular interest to this thesis. An example of how this technology could allow organisations to focus on use is described by Holmstrom & Partanen (2014) in the previous section. However, whilst illustrated, it did not highlight why it is an enabler for designing for high variety when compared with traditional manufacturing and why traditional manufacturing restricted organisations ability to design for high variety.

3D printing, also known as additive layer manufacturing (ALM), is a digital manufacturing method that produces three dimensional objects additively. It builds a physical component layer by layer from a digital file (Weller et al, 2015). This is illustrated in the following figure.

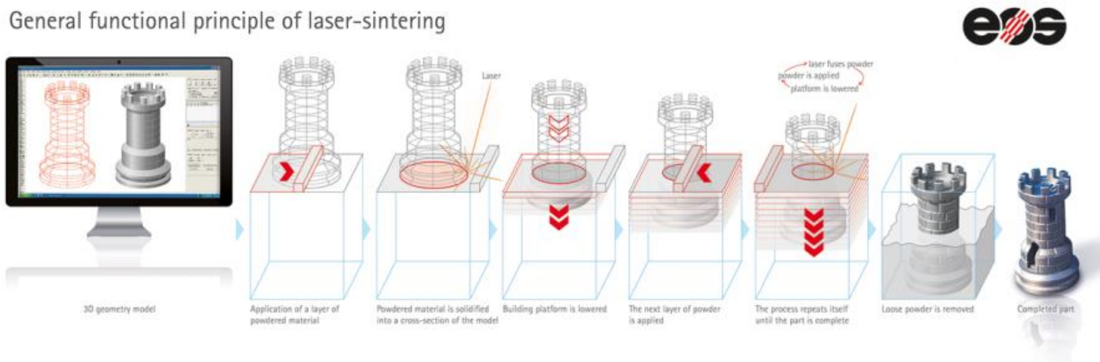

Figure 2.9. Process of 3D printing from digital file to complete component (Source: www.eos.info/addive_manufacturing).

When compared to traditional manufacturing, 3D printing has a number of characteristics that make it a suitable technology to enable organisations to implement a designing for high variety strategy. Namely, the literature finds that 3D printing has the following benefits when compared to traditional manufacturing:

- Small and medium lot sizes are feasible;
- Economies of one enables greater levels of customisation;
- No tooling is required, reducing costs and production time considerable;

- Geometric and design freedom as the production is not constrained by tooling;
- Reduction in supply chain complexity;
- Can produce rapid tooling for small batches at a more affordable price; and
- Customisation is driven by software (Holmstrom et al, 2010; Petrick & Simpson, 2013; Huang et al, 2013).

The final point is of particular interest to this thesis as it highlights the digital nature of the technology. A direct benefit of not requiring tooling to produce a component means the final output is driven by software which has two primary benefits. First, it allows a variety of customised components to be produced in a single production run at no extra cost (Holmstrom et al, 2010; Petrick & Simpson, 2013) and second, it allows the binding of form and function to be delayed until latent needs emerge so that organisations can focus on product instances (Holmstrom & Partanen, 2014; Ng, 2014). This point is particularly important when discussing the 'freezing' of design specifications. As the technology allows a delayed binding of form and function and does not require tooling that is expensive to produce, the final output does not have to be specified so early in the production cycle. Whilst it is anticipated in most industries the majority of a product will be produced via traditional technology (a standardised platform), 3D printing could be used to compliment this through the production of individualised components for specific customers' (variety and customisation at the point of use) (Holmstrom & Partenan, 2014). The result of the digital characteristics of 3D printing means these individual components do not have to be defined in the original specification that is released to the production team early on. Instead, these parts can be designed and implemented late in the lifecycle of the product and in response to customer use information. This concept is similar to the notion of incomplete product proposed by Yoo et al (2010) and product instances proposed by Holmstrom & Partenan (2014). For both, the main physical platform is standardised, but the digital layer is customisable through life and may be produced in ways the original specification did not anticipate. Thus, as highlighted by Henfridsson et al (2014), digital technology affords the ability to extend design flexibility through life whilst retaining scale economies in a way that was not achievable with traditional manufacturing. A further interesting point that can be derived from this discussion is the ability to react to customer sticky information. Delaying the binding of form and function allows organisations to be more flexible through life. In being able to react to customer information in use (Holmstrom & Partenan, 2014), 3D printing means organisations can react better to changing requirements through life as the final design is not restricted by fixed and expensive tooling and moulds used in traditional manufacturing. Therefore, technological advances afford urgency in terms of speed of change as discussed by Schilling (2000). Thus, 3D printing is a digital manufacturing process and is doing to manufacturing what digital did to phones, video and music (Ihl & Piller, 2016) with Ng (2014) suggesting it could be used to design incomplete products. Finally, Reeves (2009) found that increased connectivity would only improve the business case for 3D printing as digital files can be used to enable distributed manufacturing.

In sum, this section shows that 3D printing is a useful technology for designing for high variety contexts given the benefits that come from the unbounded materiality of digital technology. This is evident from the study conducted by Holmstrom &

Partanen (2014) and has widely been conceptualised by a number of other authors (e.g., Ng, 2013; 2014; Ihl & Piller, 2016).

2.5 Summary and key findings

This literature review has highlighted two primary approaches to design; designing for low variety and designing for high variety. In uncovering these two approaches, different purposes and philosophical underpinnings have been identified. Designing for low variety is characterised by a scientific approach to design underpinned by reductionism that specifies the complete specification of the offering prior to exchange. In creating a complete, functionally rigid offering prior to exchange, emphasise is placed on freezing the context of use where it is assumed variety of use is low. In contrast, designing for high variety is characterised by a more pragmatic or phenomenological approach to design, where value is derived in use and offerings are characterised as incomplete. Here, understanding design and context are entangled and value is created in use, it is understood that the purpose of design is to serve high variety through a functionally fluid and materially unbounded digital offering. In recognising these different approaches, the purpose of each design strategy was identified as being fundamentally different and this was primarily characterised by their alternate understanding of value and exchange. Whilst the tangible component of the value proposition is still central, these two different approaches have different ways of designing and understanding these propositions. In discussing 3D printing, it highlights an opportunity to leverage this technology for the production of individual, modified components for individuals to integrate into their context of use rapidly in order to satisfy their latent needs in use. Notably, this carries a number of implications for the organisation and their design activities as they need to consider a number of factors associated with use that were not previously considered in their design activities. These factors were brought to the fore by Ng (2013). Thus whilst on the surface designing for high variety looks like a technological challenge with respect to functionally incomplete products, it also needs to account for non-technical factors such as agency, existing resources in use, resource integration and institutions.

Within the review, S-D logic was identified as a lens through which designing for high variety could be understood. In adopting this lens, it was found S-D logic would have a number of implications for OM and our understanding of design. First, it is argued that this understanding of service as a process means service models cannot be simple extensions of existing models and methods for engineering, design, supply chain management or operations management. Instead, new, multi-dimensional ways of thinking are needed. Second, whilst not in the context of S-D logic, Hayes (2002; 2008) argued that OM needs to move beyond models of static products and processes developed within the boundary of the organisations manufacturing business unit toward understanding OM from a dynamic and expanded view of processes that occur within and across broader ecosystems, such as complex and dynamic supply chains. Furthermore, he called for the OM community to recognise and draw upon advances in other fields in order to advance theory within OM. It is argued that S-D logic, derived from the marketing discipline, would help address the concerns of Hayes (2002; 2008) in the OM discipline. Taken together, both the OM and service community are moving toward an increased acceptance that the nature of exchange occurs in dynamic and complicated ecosystems and this requires alternate perspectives of the phenomenon to be taken in order to develop relevant models, tools and theories, such as designing for high variety. Central to S-D logic is the notion of resource integration, which has been highlighted as a core component of designing for high variety (Ng, 2013). However, it was indicated that the use of resource integration as a process for underpinning designing for high variety lacked any significant theoretical underpinnings. Whilst modularity theory was identified by Ng (2013) as a suitable theoretical approach, current theory has primarily been developed within the context of modularity for low variety and therefore does not extend beyond exchange and into the customers' consumption space where value is phenomenologically determined in use. Given S-D logic and resource integration have been identified as central to our understanding of designing for high variety, it is important to review these in greater detail. Notably, resource integration in S-D logic has been approached from different theoretical angles and this may contribute toward our understanding of designing for high variety given the current theoretical approaches contained within the literature are relatively understudied. The following chapter reviews the S-D logic literature.

Chapter 3. Service-Dominant Logic and Resource Integration: A Literature Review

3.1 Introduction

The previous chapter highlighted designing for high variety was emerging as a phenomenon of interest following re-invigorated interest in value creation, as determined by the focal beneficiary, and the organisations role in supporting these value creating activities. In presenting the concept, it found compatibilities with S-D logic and resource integration. The purpose of this chapter is to review the S-D logic literature and make the case for understanding the design as a process of resource integration. In understanding design as a process of resource integration, this chapter examines existing theoretical approaches to resource integration for their strengths and weaknesses. Following examination of existing theoretical approaches, this chapter converges on modularity as a foundational theory for resource integration and justifies both its relevance and importance to organisations focussing on designing for high variety. The chapter concludes with a summary of the key findings.

3.2 A Service-dominant logic

S-D logic is a metatheoretical framework that provides an alternative lens through which complex systems of exchange made up of many interdependent actors interacting in non-simple ways can be understood and examined (Lusch and Vargo, 2014). This alternate lens has evolved significantly over the years, providing an alternate understanding of exchange and value creation underpinned by a service ecosystems[5] and an institutional perspective (Vargo and Lusch, 2016) that differs significantly to the G-D logic understanding of exchange. With the service ecosystems perspective, there is a general shift away from a linear view of value creation and exchange toward a more dynamic, emergent and complex view of exchange and value creation (Vargo and Akaka, 2012). The complexity stems from the understanding that multiple actors engage in service-for-service exchange (i.e., the application of their competencies for the benefit of oneself or another) in order to integrate and exchange resources to facilitate value co-creation (Kosekla-Huotari et al, 2016). Following advances in S-D logic, it has been argued that with the nature of exchange within and between service ecosystems being dynamic, fluid and emergent, requires a consideration of emergence, contextual variety, service system boundaries and resource integration of multiple actors to maximise the co-creation opportunity (Ng et al, 2011, Maglio et al, 2015; Vargo et al, 2017). Acknowledging the discussion in chapter 2, patterns of similarity between this and the understanding of designing for high variety are evident.

Central to S-D logic thought are the five axioms and eleven foundational premises (FP), derived from said axioms (see table 3.1). These FPs have evolved over the years to reflect the ongoing discussion and evaluation of our understanding of exchange from an S-D logic perspective. Most recently, FP 11 (axiom 5) was added following the appreciation that the nature and process of exchange is inherently systems orientated and coordinated by actor generated institutions (Vargo and

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[5] Service ecosystem is not to be confused with the service science term 'service system'. Service ecosystems prescribes a more general understanding as to the role of institutions as opposed to technology as advocated within the service science literature.

Lusch, 2016; Vargo et al, 2017). Taken together, these axioms and FPs form the central tenants of S-D logic.

Foundational Premise (FP)	**Description**
FP1 (Axiom 1)	Service is the fundamental basis of exchange.
FP2	Indirect exchange masks the fundamental basis of exchange.
FP3	Goods are a distribution mechanism for service provision.
FP4	Operant resources are the fundamental source of strategic benefit.
FP5	All economies are service economies.
FP6 (Axiom 2)	Value is co-created by multiple actors, always including the beneficiary.
FP7	Actors cannot deliver value but can participate in the creation and offering of value propositions.

FP8	A service-centred view is inherently beneficiary oriented and relational.
FP9 (Axiom 3)	All social and economic actors are resource integrators.
FP10 (Axiom 4)	Value is always uniquely and phenomenologically determined by the beneficiary.
FP11 (Axiom 5)	Value co-creation is coordinated through actor-generated institutions and institutional arrangements.

Table 3.1. Foundational premise and axioms of a service-dominant logic (Adapted from Lusch & Vargo, 2014 and Vargo & Lusch, 2016).

Whilst seemingly mature, S-D logic is not without its criticisms. Namely, it has been criticised for having a lack of relevance for practitioners (O'Shaughnessy and O'Shaughnessy, 2009). Within the OM community, it was criticised for not providing a balanced view of both the provider and the customer (Sampson and Menor, 2011). Sampson and Menor (2011) further argue that S-D logic does not provide enough insight into the operational challenges often found within the context of a service and non-service. Finally, in an interview with Dick Chase, Smart & Alves (2014) found that whilst S-D logic is a good philosophy in that the primary purpose of an organisation is to serve a customer, for an operations scholar is it a logic that is difficult to comprehend and work with. However, the continued expansion of S-D logic has seen a number of recent articles derive operational requirements, mid-range theories and managerial insight to enhance an organisations ability to manage service provision and provide insight into operational challenges (e.g., Michel et al, 2008b; Pawar et al, 2009; Lusch, 2011; Ordanini & Parasuraman, 2011; Smith et al, 2014; Lusch & Nambisan, 2015; Skalen et al, 2015; Ng et al, 2015; Parry et al, 2016; Nowicki et al, 2018) suggesting it is a mature frame through which phenomenon can be explored.

Following acceptance of S-D logic as a mature frame through which to explore the phenomenon, it is important to discuss it within the context of this thesis. Chapter 2 brought to the fore the concept of designing for high variety and in doing so found compatibilities with S-D logic. Within the literature, It is said that the implications of S-D logic is that new models and frameworks for service are needed as those developed for product design, engineering and supply chain management developed over the course of the past six decades may not be applicable (Ng & Nurudupati, 2010; Ng et al, 2011). This is supported by Ordanini & Parasuraman (2011) who found that existing G-D logic approaches actually limited the ability of academics to glean insight into the more complex and nuanced nature of service innovation, leading them to promote S-D logic as an appropriate lens through which to study the phenomenon and derive more relevant and comprehensive theories for innovation. Based on these assertions, it is important to account for the literature that has addressed design from a S-D logic perspective. This is now discussed in the following section.

3.2.1 Service-dominant logic and design

Design has not been a prominent topic within the S-D logic literature. However, within the work that has been conducted, the primary themes throughout the literature are value creation, resource integration and institutions.

Michel et al (2008b), in their discussion of innovating customers and not products, highlight that changing the discussion from value in exchange as created in an organisations design and production activities to value in use as defined by the customer, is what defines design and innovation. In recognising the implications of this alternate perspective of value, they argue that the premise of design is recognising the organisations design activities enable customers' to find new ways to service their needs. In addition, they characterise design as a process of identifying new ways of co-solving customer's latent needs and that this requires the integration of resources from two or more parties within the value constellation.

Within marketing, Edvardsson & Tronvoll (2013) draw insights into service innovation, grounded in S-D logic, from structuration theory. They highlight that because value unfolds in practice, customers' are the primary actor within service innovation. This corresponds with the understanding of design and innovation presented by Michel et al (2008b). They build a tentative conceptual framework of service innovation based upon the postulate that innovation is defined as "*changes* *in structure that stem from either a new configuration of resources or a new set of schemas and that result in new practices that are valuable to the actors in a specific context" (pp. 24).* Schemas being rules, norms, practices and other institutions as discussed by the mainstream S-D logic literature (e.g., Vargo & Lusch, 2016). Their framework is presented in the following figure.

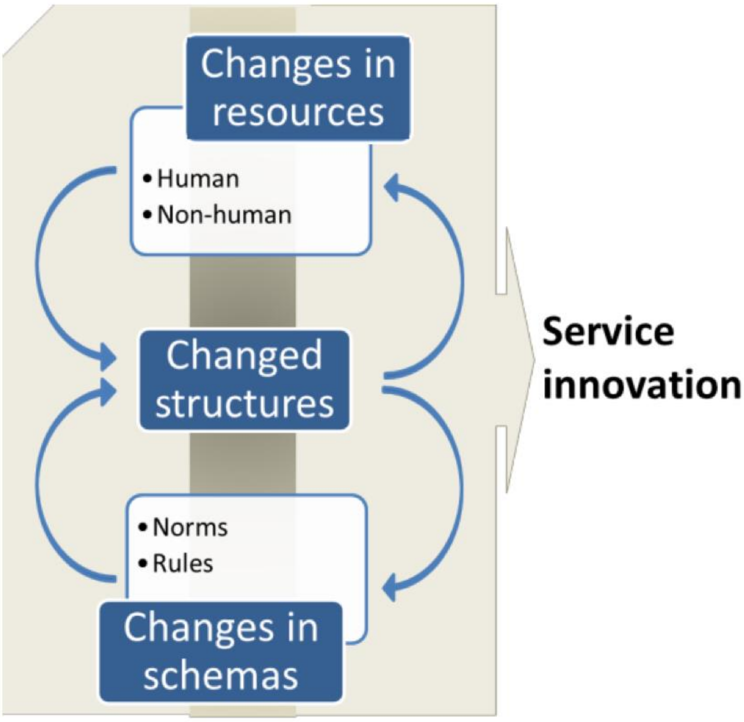

Figure 3.1. A framework for service innovation grounded in service-dominant logic (Source: Edvardsson & Tronvoll, 2013).

They propose that innovation can only be studied in use, because this is where value is co-created and assessed over time and therefore, innovation is always centred on the practices of the focal beneficiary within a specific context of use. Therefore, their framework emphasises that innovation occurs when changes to either resources, structures or both occurs within the focal beneficiaries context of use. This suggests organisations design and innovation activities should focus on creating changes to resources or schemas within the focal beneficiaries' context of use in order to maximise resource density and value creating opportunities. Furthermore, it brings to the fore a change in emphasis from focusing design activities on individual resources with respect to their functionality toward creating a *"configuration of resources" (*pp. 27*)* available for the user to integrate and operate upon, creating value for both the focal beneficiary and other members of the service system.

The premise of their study highlights consistencies in our understanding of design across the S-D logic literature. Edvardsson & Tronvoll (2013), Ng et al (2011), Ng (2013), Maglio et al (2015) and Vargo et al (2017) all suggest it requires organisations to consider emergence, contextual variety, system boundaries and resource integration of multiple actors. Considering these factors as effecting value creation, Maglio (2015) puts forward that resource requirements may not be possible to predict in advance due to the dynamic and emergent properties of use and this has implications for the organisations. As noted earlier, a number of authors posit that the rise in digital technologies will allow organisations to focus on use where emphasis is placed on dynamic resource integration and value in use (Ng, 2013; Maglio et al, 2015; Parry et al, 2016) with the Internet of Things (IoT) supporting the demand side and 3D printing supporting the supply side (Maull et al, 2015).

In a more recent study, Lusch & Nambisan (2015) address service innovation in the digital age, with particular attention given to management information systems and digital service platforms. Within their study, they define service innovation as *"being embedded in an A2A network and begin with the notion of service ecosystems, which underscore the importance of common organisational structures to facilitate resource integration and service exchange among those actors"* (pp.161). Based upon their expanded view of service ecosystems, they proposed the following framework for service innovation in a digital age.

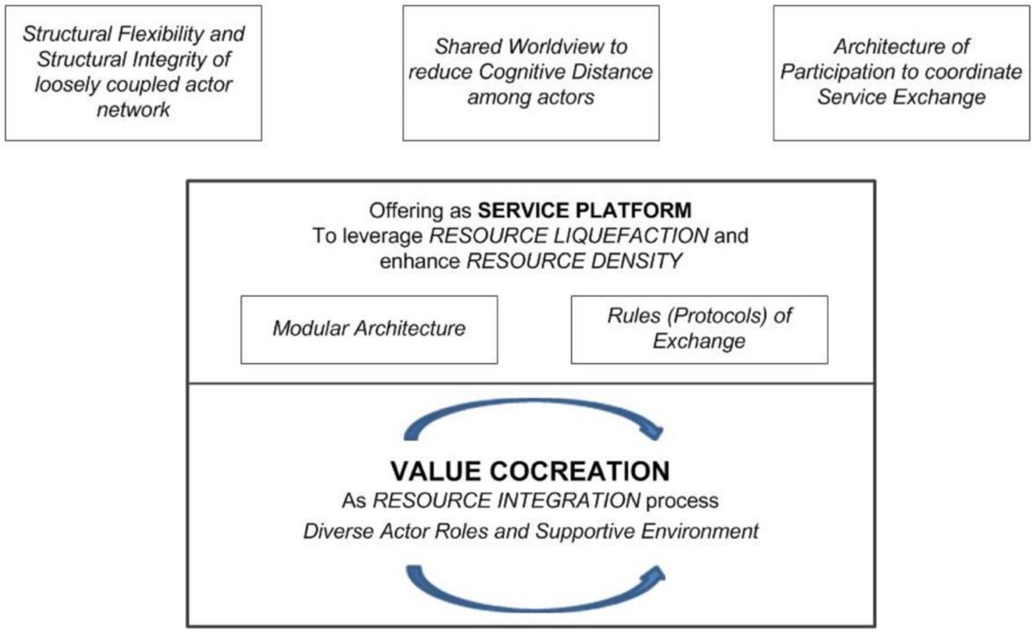

Figure 3.2. A framework for service-dominant logic service innovation in the digital age (Source: Lusch & Nambisan, 2015).

This framework provides an important step toward a more broadened view of service innovation focussed on liquification and resource density (Normann, 2001) in the digital age. Emphasis is placed on resource integration and institutions facilitated by service platforms (i.e., digital platforms) comprised of both tangible and intangible resources that aid interactions between both actors and other resources within the service ecosystem. In contrast to product platforms, where emphasis is on systematically defining the whole prior to exchange, digital platforms take advantage of resource liquification for the purpose of enhancing resource density for the focal beneficiary. Underpinning an organisations ability to enable resource density is the concept of a layered-modular architecture (Yoo et al, 2010). In contrast to design hierarchies as defined by Clark (1985), whereby modular architectures draw on components from a single design hierarchy (i.e., the product has a hierarchy of modules with specific functions that the product can perform through life, fixing the functional boundary of the offering in the design stage), a layered modular architecture can draw on different design hierarchies across different layers meaning components are not bound to a single product in the way they are in a strict modular architecture. Thus, functionality of a product is more flexible than those with a single design hierarchy. That is, components contained with a modular layered architecture are not bounded by a single offering and are therefore product agnostic (Yoo, 2013). Thus, technologies such as 3D printing allow offerings to exhibit differences in kind as binding of form and function is temporal and almost permanently delayed (Yoo, 2013) whereas strict modular architectures are only able to exhibit differences in degree. In the context of S-D logic, a layered modular architecture allows components to be represented as sets of competencies (knowledge and skills) that can interface with heterogeneous, as opposed to homogenous, forms of value propositions.

Within their study, they make specific reference to resource integration and design as facilitating value co-creation and that this is central to their framework. They highlight designer as one of three roles the customer plays within resource integration and value co-creation. Designer refers to the ability of the focal beneficiary to mix and match existing resources (tangible or intangible) into a specific configuration that services their needs. Therefore the role of the designer is in resource configuration and the process of design is to present resources to the service ecosystem that can then be integrated for value creation. Notably, they place emphasis on the beneficiary as the designer and that their role is to explore and/or discover either common or uncommon combinations of resources that fulfil their needs with the organisations within the value constellation facilitating this.

The discussion of Lusch & Nambisans (2015) framework has emphasised the central portion of their framework; modular architecture, rules of exchange and value co-creation. Whilst the other three components at the top of the framework are useful in a broader discussion of service-for-service exchange in a digital economy, they are outside the scope of this thesis. However, the concept of shared world view is important to reflect upon. The authors refer to shared world view and adopting a shared understanding of things, such as business or cultural assumptions. Simply, a shared world view reflects the service ecosystem having a common perspective of their environment, each actor's role within it and how they can contribute and exchange between one another to maximise the efficiency and effectiveness of the service ecosystem. From this description, it is possible to draw comparisons of the use of the term shared worldview and design rules as discussed by Baldwin (2008) in the context of modularity theory. A deeper discussion of design rules is presented in section 3.4. From here on in, design rules will be the term used to reflect 'shared world view' and can be used to reflect a common understanding between modules at different levels of aggregation i.e., product, service, organisation or ecosystem level.

3.2.2 Summary of service-dominant logic and design

Throughout both this section and the previous chapter, it has been highlighted that resource integration is a foundational component of S-D logic as it is related to design, value co-creation and system viability. In particular, Lusch & Nambisan (2015) explicitly discussed design with respect to the focal beneficiary and their ability to act as a designer is facilitated by their competence to integrate resources from various members of the service ecosystem. They highlight that the possibility of heterogeneous resource integration enhanced by increased levels of digitisation. With respect to theory, consideration was given to both modularity, structuration and institutional theory, but the studies presented appeared to lack significant depth in applying and explaining the role of these theories in their understanding of design from the perspective of use and resource integration. Notably, all authors brought to the fore how the changes in our understanding of value alters our perception of design and in particular, the relationship between resource integration and design. However, whilst resource integration is central to S-D logic and has been given considerable attention in the literature, it has not been grounded in a solid theoretical foundation and thus the discussions around resource integration are often limited to generic descriptions of what resource integration is and how it broadly enables value co-creation to take place (Peters et al, 2014). As a result, the following section discusses resource integration in greater detail before examining existing theoretical perspectives in detail.

3.3 Service-dominant logic and resource integration

The main premise of S-D logic is that service is exchanged for service in order to co-create value through the provision and integration of resources within the service ecosystem. The purpose of constant adjustment of resource requirements shows the primary purpose of exchange is to improve viability of a system through density maximisation (Lusch and Vargo, 2014).

Resource integration is broadly defined as the process of integrating and transforming '*micro-specialized competences into complex services that are demanded in the marketplace', and which perform particular service system functions for a specific beneficiary or actor in the service system'* (Vargo and Lusch, 2008. pp 7). Resources (competences) within this context are not confined to operant and operand resources developed by man and culture, but also non-physical entities such as time, environmental conditions, laws, rules and regulations are often relied upon for value creation (Vargo et al, 2010). This definition also leads to the understanding of resource integration as a process whereby activities are performed by an actor or actors within the service ecosystem for the benefit of themselves or another (Vargo & Lusch, 2004; Payne et al, 2008). This understanding of resource integration and resources as becoming when acted upon (Zimmermann, 1951) reflects an understanding that resources are carriers of competence and when acted upon allow an activity to be performed for the purpose of value creation (Lobler, 2013; Peters et al, 2014). To illustrate this, an example can be drawn from the Rolls Royce Power by the Hour concept within the servitization literature (Baines et al, 2009a). Within this context, an engine is only an engine and potential resource until integrated and acted upon by the customer and their operant resources to produce propulsion and allow the actor(s) to transport passengers to their chosen destination. In this example, they also draw on weather conditions and time within their value creating activities.

The discussion so far shows compatibilities between designing for high variety and resource integration and suggests there is a relationship between the two. In discussing designing for incompleteness (high variety), Garud et al (2008) highlighted that designs (resources) are simultaneously a noun and a verb. They also state that every outcome (i.e., design or manufactured offering) marks the start of a new process once integrated and acted upon by various actors within their use contexts (Kimbell, 2011). Combining this understanding of design with the five attributes of use that Ng (2013) highlighted as being essential if an organisation is to design for high variety as opposed to exchange (low variety), provides a more holistic and complete understanding of the requirements of designing for high variety. Taken together, if an organisation first acknowledges and understands the customers' existing value creating activities, as discussed by Payne et al (2008), Gronroos & Ravald (2011) and Ng (2013), then they can best position themselves to design a suitable value proposition, underpinned by digital technology, that can be adapted, modified and bespoke within each individuals use context. Thus, design is a process of resource integration that is simultaneously a verb (resource integration as a process) and a noun (the resources to be integrated) as determined by the focal beneficiary.

3.3.1 Lack of theoretical underpinnings

The previous section discussed resource integration and resources from a S-D logic perspective and illustrates their relationship with designing for high variety. Whilst they appear well developed and logical, many of the descriptions contained within both this thesis and the wider literature lack significant theoretical grounding. This is observed by Edvardsson et al (2014), who note that the process of resource integration and coordination of resource integrating actors is a relatively understudied area of interest. This is an interesting proposition given Wilden et al (2017), in their review of past, present and future S-D logic research, found resources and resource integration were two of the most consistently discussed concepts within the S-D logic literature between 2004 and 2015. However, from this literature review thus far it can be argued that whilst discussed, little theoretical consideration has been given to the process of resource integration. This is supported by Peters et al (2014) who argue that the definition of resource integration provided by Vargo & Lusch (2008) is not actually that useful as it is merely a generic description of the concept. Within their review of the literature, they found over 100 papers by 2012 had discussed resources and resource integration within S-D logic. However they found only 15 articles adequately theorised around the concept and even then questions were raised about the significance of the theoretical discussions and contributions contained within said papers. Finally, Pohlmann & Kaartemo (2017) highlight that theoretical contributions to resource integration in S-D logic are not currently well developed, but if it was it would help toward the understanding of other core principles of S-D logic given the centrality of resource integration to value creation and service-for-service exchange.

These articles bring to the fore the shallow theoretical underpinnings of resources and resource integration even whilst it is such a central concept to S-D logic. At present, S-D logic is calling for greater emphasis to be placed on the development of mid-range theory (Brodie et al, 2011) with these types of study emphasising the development of some propositions for others to empirically explore (Brodie & Gustafsson, 2016). Lusch et al (2010) note that mid-range theories for resource integration in the areas of design science and design thinking would be a novel area of application for S-D logic. Furthermore, Brodie et al (2011) suggest that mid-range theory would help bridge the academic-practitioner divide and that four of the ten FPs (see table 3.1) are core to the development of mid-range theory.

Within the previous chapter, Ng (2013) claimed modularity theory as conceptualised by Baldwin (2008) would be a suitable theoretical approach for design and resource integration. However, whilst S-D logic recognised modularity in earlier evolutions of the logic, it was not developed to a suitable level to inform the process of resource integration. Building upon the foundations already laid by earlier scholars and drawing upon the lens of S-D logic, an opportunity to develop a mid-range theory for S-D logic within the specific scope of design and modularity is evident.

3.4 Modularity theory

As discussed within chapter 2, modularity has primarily been discussed as a strategy for managing complex products and processes efficiently, with emphasis placed on systematically designing and producing complete products or services. As with previous definitions, complex products and processes are simply those products and processes made up of many interdependent parts that interact in non-simple ways (Baldwin & Clark, 2000). Within this context, modularity was generally discussed from the perspective of a noun (i.e., a functional attribute). The emergence of service modularity saw a number of scholars within the OM community conceptualise modularity as a process (i.e., a verb). For example, Starr (2010) saw modularity as 'loops of activities' whilst Rahikka et al (2011) discussed modularity as a process made up of tasks that perform specific functions. These definitions align with the OM and S-D logic rhetoric and the understanding of design being both a noun and a verb where the output of each activity indicates the start point of another design process (Garud et al, 2008). However, whilst service modularity has emerged as a phenomenon of interest, it primarily conforms with the top left quadrant of Kimbell's (2011) framework, what Garud et al (2018) term designing for completeness and what this thesis has termed modularity for low variety.

In a broader study of modularity, Baldwin (2008) integrated the theory of the firm, transaction cost economics (TCE) and modularity theory to conceptualise where transactions take place within a system as TCE does not currently address this area. At the centre of this theory was the concept of modules, module boundaries and thin and thick crossing points where resources are exchanged and integrated between different participants of the system. Within her study, she highlights how participants of production are constantly transferring and exchanging energy, information and material between two parties at a crossing point located at a module boundary (Baldwin, 2008). She describes crossing points as either thin or thick with thin being the best location for transactions, where what is to be exchanged can be easily counted, measured and verified for efficient service-for-service exchange. In contrast, thick crossing points are found within modules where lots of complex interactions between elements of the module take place and requires actors to have a deep knowledge of the task or process to be performed. These are called transaction free zones and are a space where a designated set of transactions can freely occur within a physical or social space (Baldwin, 2008). Baldwin illustrates her theory in figure 3.3 using the example of a pot hook design (a pot hook is a metal hook used for lifting a hot pot in a kitchen) and a transaction between a smithy (a worker in metal who produces the pot hook) and a kitchen (where cooks use the pot hook to handle cooking pots). The transaction that takes place is of the completed pot hook that the smithy has the competences to make and the cooks have the competence to use. Between them, they have a shared understanding of what a pot hook should look like and what its primary function is, but as noted, one has the competence in producing and one has the competence in using and this determines their 'module' within the production system. However, having a shared understanding is important as this is what informs the design rules, labelled S1-S5 and K1-K5 on figure 3.3. These design rules mean that their shared understanding allows the smithy (labelled S) to produce the pot hook independently of the kitchen (labelled K) and the kitchen to use the pot hook independently of the smithy. The only point of interaction is the pot hook transfer, which is easily defined, verified and counted (i.e., it is simple to exchange and therefore a thin crossing point), and this process of exchange is supported by the design rules that allow independent working and a simple exchange between the two parties. In contrast, if they did not have a shared understanding (i.e., no global design rules), interactions between the two would be increasingly complex and overlapping, interacting in non-simple ways but not bounded by module boundaries capable of containing and managing said complexity. It is important to note that whilst this simple example shows a set of shared global design rules, it often takes time for these design rules to emerge (Baldwin & Clark, 2000).

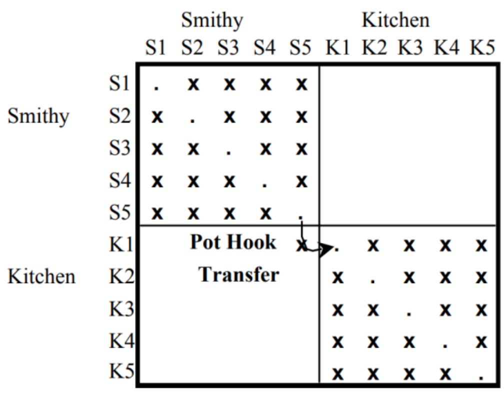

Figure 3.3. Modular theory of the firm (Source: Baldwin, 2008).

The image in figure 3.3 is intended to show how the modularisation of each individuals (smithy and cook) activities makes the transaction (i.e., of the pot hook) easier to count, define and verify. Within each module are the complex design decisions that are hidden from the others module (i.e., information hiding). These decisions for the smithy include the design and production of the pot hook (i.e., their function is production), which the cooks do not have. For the cooks within the kitchen, their decisions revolve around how to use the pot hooks, when to use them, what to cook, how to cook it and so on. Thus, each module reflects a division of labour where each party has a specialised competency that the other does not and it is better to keep them separated for the efficiency of the system. Using the lexicon from S-D logic, actors participating in service-for-service exchange, seek to exchange and integrate their resources at a thin crossing point (i.e., a module boundary). Between the smithy and the kitchen there is almost complete independence beyond the material connection as they are guided by the design rules that govern the system. Drawing on product modularity literature, Baldwin (2008) defines design rules as a shared understanding of the systems functions and interfaces so that efficient and effective communication and exchange between modules can take place. In particular, figure 3.3 design rules reflect the mutual understanding of what a pot hook is made of, what it looks like and what its function is to be. This allows each module to conduct their activities individually, with little to no communication other than the exchange of the pot hook at the module boundaries Thus, assuming the global design rules adequately represent both parties' roles and requirements within the system, the two can operate almost independently of one another whilst maintaining viability of the system through resource integration. It is possible to attribute the design rules to the ecosystem's institutions, where overlapping and nested institutions enable the efficient and effective integration of resources between parties (Hartmann et al, 2018). However, this view proposed by Baldwin (2008) is simplistic and focusses on production chains that lead to a narrow, static view of how modularity allows service-for-service exchange to occur (Spring and Araujo, 2009; Ng, 2013). Furthermore, it assumes completeness in design prior to exchange as the context within which Baldwin (2008) articulates her study is static production systems where a complete separation of design and context (use) exists.

Within the S-D logic literature, modularity, as discussed by Baldwin (2008), was discussed during its earlier expansions (e.g.,Vargo, 2009; Vargo and Lusch, 2010) and by Lusch & Spohrer (2012) as being an important theoretical underpinning for the creation of modular structures that allow resource integration to efficiently and effectively take place. With the emergence of institutions as the unifying theory for resource integration within the S-D logic literature (e.g., Edvardsson et al, 2014; Lusch & Vargo, 2016), modularity appeared to have been forgotten. However, both contemporary and historical literature suggests it is worth pursuing a broader understanding of modularity, as described by Baldwin (2008), to help understand the process of resource integration (Hartmann et al, 2018) and how, in an era of digitisation, it can help organisations design for high variety (Ng, 2013). This was brought to the fore by Ng (2013) who highlighted that a customer's use context is currently a transaction free zone that organisations struggle to serve efficiently and effectively. Three primary reasons for this were given by Ng et al (2015). (1) Information is asymmetric as organisations have less information about use than users do. (2) Complexity in information aggregation as the organisation may not be able to sort and analyse the use information to engage in mass customisation. (3) Incomplete information about future desired outcomes. From the review of the literature thus far, a further item can be added that prevents organisation's efficiently and effectively engaging in design for high variety. This is: (4) Traditional manufacturing techniques used to design and produce material assets do not equip the organisation with the affordances and benefits associated with the unbounded nature of digital materiality. However, the rise of digital technologies, such as IoT and 3D printing, means the organisation could change the design of their value proposition so that a thin crossing point is created in use and customers, who are most knowledgeable about use, can use their resources to integrate and modify the asset according to the desired outcome. However, whilst Ng (2013) highlights the importance of modularity, resource integration and digital technologies for designing for high variety, her examples are primarily illustrative. Thus, whilst modularity is advocated as an appropriate theory for understanding how to design for high variety, she calls on the research community to move modularity beyond static production systems described by Baldwin (2008) and theorise from the perspective of S-D logic where exchange is more complex, dynamic and focussed on use and outcomes and underpinned by digital technology.

Within OM, Spring and Araujo (2009) present this as an opportunity to change the role of the operations manager and how they design products and processes. They highlight how the identification and creation of module boundaries and thin crossing points is an increasingly important task for the operations manager. In particular, they highlight that if they are able to modularise the system to create module boundaries and thin crossing points, transaction costs lower and result in a more efficient system through which the beneficiary can purchase or access resources for value creation. That is, where previously thick crossing points existed, such as within the contextual experience, emergent changes in technology or other elements of the system may result in the ability to turn once thick crossing points into thin crossing points. Deciding on where thin crossing points should be throughout the ecosystem is therefore a fundamental challenge for product and process design within OM (Spring and Araujo, 2009).

The totality of the above argument would suggest that modularity is a more general theory for resource integration, with institutions adopting the role of global design rules, resources acting as modules and the service ecosystem the architecture. Furthermore, following the discussions of design by Michel (2008b) and Lusch & Nambisan (2015), it can be argued that design focussed on value in use and supported by digital technologies would allow actors to use their agency and resources to integrate digital resources to temporarily bind form and function of their value proposition as and when required. However, whilst this proposition is supported by contemporary literature (e.g., Ng, 2013; Holmstrom & Partanen, 2014; Hartmann et al, 2018), it is clear it remains an area that is understudied, suggesting a theory building approach is suitable for this thesis. From here on in, modularity with respect to designing for high variety will be labelled modularity in context.

3.5 Toward a foundational theory for modular resource integration

From this review of the literature, a number of contributions toward understanding designing for high variety as a process of resource integration have begun to emerge.

The most notable contributions are from Baldwin (2008), Spring & Araujo (2009), Ng (2013) and Hartmann et al (2018) where they conceptualised modularity as a process as opposed to a property of functionally static architectures as discussed within mainstream management literature (i.e., Ulrich, 1995; Baldwin & Clark, 2000; Fixson, 2005; Salvador, 2007). Considering themes within the literature, modules, module boundaries, resources, resource integration, design rules and crossing points are seen as particularly important concepts that form a foundation for modular resource integration and coupled with the factors associated with use as proposed by Ng (2013), form a foundational understanding of designing for high variety. Most notably, it was found that a challenge for OM was in identifying where thin crossing points could be created, how organisations could subsequently create them and how technology could support this (Spring & Araujo, 2009). In identifying this, Spring & Araujo (2009) suggested this was one of the more important considerations for operations managers with respect to product and process design.

3.6 Summary

This analysis of the S-D logic and resource integration literature has highlighted a lack of theoretical understanding of the determinants of resource integration and the subsequent effect this has on being able to understand how we can design for high variety. Whilst contemporary literature has begun to pay more attention to the theoretical underpinnings of resource integration, there is disagreement around its foundational concepts. Whilst mainstream S-D logic has argued that institutional theory provides the most comprehensive theoretical understanding of resource integration and the act of value creation more generally, this thesis has found evidence to suggest it forms only part of the process. In contrast, this thesis found both resource integration and design share common interests in modularity theory. This provides a novel opportunity to build theory that could help inform organisations designing for high variety, which remains an understudied area of interest within the literature. This is especially prevalent within the digital economy, where resource mobilisation and integration is almost limitless, allowing organisations to focus on use and context and the design and creation of thin crossing points within the contextual experience (i.e., customers' use context) supported by digital technology.

Finally, throughout both chapters 2 and 3, servitization has been discussed as a context within which questions around designing for low variety are being raised, leading scholars to call for more research in the field of designing for high variety where it is argued new, multi-dimensional ways of thinking are needed. As a result, the following chapter explores servitization as an appropriate context within which to build theory around resource integration and designing for high variety.

Chapter 4. Servitization as Context: A Literature Review

4.1 Introduction

This section introduces servitization as the context within which this study takes place. Throughout chapters 2 and 3, reference has been made to servitization as being an exemplar for focussing on use and outcomes where value is co-created in context. Thus, providing a novel area through which the phenomenon of designing for high variety can be explored. This chapter begins by providing an overview of servitization and its common definitions. Second, it discusses the opportunities servitization provides in exploring the phenomenon before highlighting some existing concerns within the literature about the relevance of designing for low variety in a servitized context, where the focus is on use and outcomes. Finally, this section concludes with a summary of the major findings presented within this chapter.

4.2 Servitization overview

Servitization has become an increasingly popular phenomenon within both academia and practice. Servitization is generally seen as the transition from selling a product to providing a service (Vandermerwe & Rada, 1988; Baines et al, 2009b). Inherent in this transition is the appreciation that an organisation's focus shifts from value in exchange to value in use (Baines et al, 2007). In acknowledging this shift, it is evident that there is a move away from the traditional transactional exchange between firm and customer, to a longitudinal relationship centred on product service systems (Smith et al, 2014).

Many manufacturing firms have now designated service business units and provide a range of service types as an extension of their manufacturing capabilities. The rationale behind this is that as manufacturing revenues have begun to decline, servitization provides an opportunity for organisations to create additional value and improve their competitive advantage through the provision of services (Baines et al, 2009b). This provides an opportunity to improve profit margins, create customer lock in and enable greater differentiation rather than competing with others on cost alone (Gebauer et al, 2011; Bustinza et al, 2015). As a result of this increased attention, facilitating servitization has recently become a service research priority (Ostrom et al, 2015).

The servitization literature has inherently focussed on the product-centric servitization (Baines et al, 2009a) where the physical asset is central and the services provided are wrapped around and coupled to the existing asset (Baines et al, 2009b; Ng & Briscoe, 2012). Thus, the service activities were seen as the phenomenon of interest for the academic community and this is reflected in the vast body of knowledge contained within academic journals. For instance, Baines et al (2009a) stress that the addition of service activities necessitates that organisations need to transform existing organisational structures and processes to accommodate the differences between products and services. This has led to a number of scholars focussing on business model innovation and organisational, structural and cultural changes brought about by the new service activities (e.g., Martinez et al, 2010; Hypko et al, 2010; Selviaridis & Wynstra, 2014; Vendrell-Herrero et al, 2014; Bustinza et al, 2015; 2017; Visnijc et al, 2016).

In terms of focus and a shared understanding of what servitization is, the academic community agree that Vandermerwe and Rada's (1988) definition is one of the first and most comprehensive definitions of servitization. Whilst not all disciplines (i.e., marketing, design, operations management, ecology etc) utilise the same label, they predominantly align with the original definition whereby manufacturing firms 'add' services to existing product offerings and create a value proposition that is a mixture of both product and service components. In addition, Vandermerwe and Rada's original definition explicitly pointed toward an increased customer focus.

An analysis of the literature presents some key defining features associated with the three dominant terms used within the management community; servitization, service infusion and product service systems (PSS). A PSS can be defined as '*a market proposition that extends the traditional functionality of a product by incorporating additional services* (Baines et al, 2007. PP. 1544). First, servitization and service infusion are arguably the most interchangeable as they are both associated with the 'transition' from a manufacturer to a service provider. That is, both research streams are concerned with the continuum of which manufacturers move along as they 'servitize' or 'infuse services' into their existing business. This notion of a continuum implies that there are varying degrees of product and service configurations across the continuum and it is these configurations that make up the different types of PSS. Baines et al (2009a) explicitly state this and make clear reference to PSS's in their definition of servitization. Thus, it can be argued that servitization and service infusion are associated with the transition from manufacturer to service provider whilst the PSS is the value proposition offered by the firm to the customer and the PSS can vary in degree of product and service components. This is the understanding of servitization and PSS that will be used within this thesis.

Within the literature, it appears that most authors agree that servitization was based on an emerging phenomenon within industry and whilst studied from different disciplines, they all share common characteristics and principles. First, they are all underpinned by the acceptance that manufacturing firms are paying more attention to service and different forms of value proposition are made up of varying degrees of product and service components (e.g., Robinson et al, 2002; Mont, 2002; Oliva & Kallenberg, 2003; Tukker, 2004; Ulaga & Reinartz, 2011; Baines & Lightfoot, 2013). Second, is the common understanding that the shift to service embodies a departure from a value-in-exchange to value-in-use and customer centricity (Green et al, 2017). Third, the appreciation of the increasing importance of technology as an enabler of service is gaining considerable popularity. Neely (2008) states that as technology continues to advance, it will not only be an enabler for service, but a driver for new types of service. This is reflected in Dinges et al (2015) report on technologies in servitization. Fourth, that the transition from manufacturing to service and the provision of a PSS could change the roles and relationships between the ‘firm’ and ‘customer’. In shifting from an exchange mind set to one based on use, reflects the customer gaining value in the use of the offering, as opposed to the ownership of the offering and that this change requires reconsideration of each party’s role and relationship (Ng et al, 2013). Finally, and one of the more recent themes to emerge within the literature is that the design of a PSS (Morelli, 2006; Maussang et al, 2009), and in particular the role and understanding of the physical asset within servitization, requires new tools, methods and theories than when the offering was designed for exchange (Ng & Nurudupati, 2010; Smith et al, 2014; Green et al, 2017). This means that servitization may force a re-design of the physical asset itself to incorporate human activities associated with use and context (Ng, 2013; Smith et al, 2014; Green et al, 2017). Given its relative newness, this last theme has received little empirical attention within the literature.

4.3 Servitization as context

The previous section introduced servitization and gave a broad overview of its main underpinnings and areas of interest within the literature. The final paragraph highlighted a number of points that make servitization a relevant concept within which to study the theoretical underpinnings of designing for high variety as a process of resource integration.

Much of the servitization literature is developed from an OM perspective and emphasis is placed on the design of the PSS and the digital technologies that support said PSS (Ostrom et al, 2015). However, evidence from the literature suggests that whilst a fundamental shift in understanding of value has occurred within the literature, it has not influenced the way in which the organisation approaches the design of the value proposition, with emphasis here placed on the material component of the proposition (i.e, the physical asset). For example, Green et al (2017) found within their review of the servitization literature that both a G-D logic and S-D logic converge on the idea that servitization requires an organisation to optimally configure both human and material resources for the design of their value proposition. However, it is argued that a G-D logic approach has largely ignored the physical assets role within servitization, placing emphasis on the new service activities that wrap around the physical asset (Ng & Briscoe, 2012; Spring & Araujo, 2017). This is driven by their understanding of value-in-use. Recognising service activities as the 'main differentiator' has resulted in them being seen as the primary component of the value proposition that assist in customer usage and deliver value (Vandermerwe & Rada, 1988; Verstrepen & van Den Berg, 1999). This view has resulted in the new services activities being the focus of academic literature to date as it is assumed that existing manufacturing theories, tools and methods for the physical asset are appropriate for a servitized manufacturer (Ng & Nurudupati, 2010). This is reflected in recent articles by Baines et al (2009b) and Visnjic et al (2016) where they discuss service activities as facilitating product autonomy and facilitating the automation of client processes through the efficient running of the product. Based on this discussion, it can be deduced that the role of the physical asset is to remain functionally stable, through efficient operation of existing functionality, and to deliver value to the customer. This corresponds with Green et al (2017) who find that the G-D logic literature still fundamentally understands value as exchange and something the firm can create and deliver in use, as opposed to the S-D logic literature that sees value as being phenomenological determined in use. Based on this analysis, it can be determined that servitized manufacturers currently conform to a scientific approach to design as the organisation places emphasis on a complete physical asset prior to its use.

Even whilst product innovation is explicitly discussed within the context of servitization, the understanding of the product as a stable platform for service delivery remains prevalent (Spring & Araujo, 2017).

In recognising that the physical asset may be best placed to absorb variety (Ng & Briscoe, 2012; Smith et al, 2014), a number of authors have highlighted how using existing manufacturing theories, frameworks and tools that emphasise completeness and functional rigidity may negatively affect organisational performance as the design approach they use is not suitable for the business model it is operating within (Ng, 2013; Smith et al, 2014). First, Ng & Briscoe (2012) note that this approach to design may have been contributing to the service paradox because the design cannot accommodate variety in use and this forces organisations to rely on human resources that are inherently not scalable across contracts. They highlight how organisations have recently come to the realisation that the physical asset in use is within the boundaries of their service system and in recognising this, they have accepted that a redesign of the asset could allow the asset to absorb contextual variety and subsequently effect the human activities used in service provisioning. Whilst their study did not provide any recommendations for the re-design of the asset to absorb variety, it is possible to draw on studies by Ng (2013) and Holmstrom & Partanen (2014) to see how organisations could leverage digital technologies to support the assets ability to viably modify its functionality in use as and when required by the customer. Second, Ng (2013) and Green et al (2017) posit that this is because organisations are using legacy products that were designed for a business model of exchange within business models focussed on use. They highlight that this is paradoxical as the two different business models have different requirements for design and placing an asset designed to be functionally static and complete in a context characterised by high variety is not desirable given they have different requirements. This conforms with earlier work by Ng & Nurudupati (2010) who argue the linear, bounded and sequential methods of production are not appropriate for servitized contexts and instead new multi-dimensional and fluid ways of thinking are needed. Furthermore, it aligns with the two design approaches discussed in this thesis. The legacy assets would have been designed for low variety, given they were designed prior to the organisation servitized and their focus was therefore on the separation of design and context, whereas the context within which they are now used is one that would be more suited to a designing for high variety frame. Smith et al (2014) adds that servitization requires organisations to incorporate human activities in use into their design activities and that if they are not, the design may be contributing toward the service paradox as it is not suited to the context within which it resides. Finally, Holmstrom & Partanen (2014) propose digital technology, such as 3D printing, would enable organisations to focus on product instances. However, they state that this requires novel approaches to design that may not conform with existing thinking as it emphasises use and context, where the organisations asset, 3D printer and customer resources are all present in use.

Based on the above discussion, it is possible to decipher that in certain contexts, where the organisation operates in environments characterised by high levels of contextual variety (i.e., characterised by continuous change), a designing for high variety frame would be appropriate. An example of this is the recent Afghanistan and Iraq campaigns within which the UK military was involved. Within this context, the asset (i.e., their armoured vehicles) was exposed to high variety of use as it was designed for a different context of use and as a result, a number of design changes were required to accommodate said variety and optimise resource density for the achievement of outcomes. In contrast, in environments characterised by low variety, a designing for low variety frame would be appropriate as the context within which the asset is used is not characterised by continuous change. An example of this is the printer management system presented by Baines et al (2007) within their study of PSS. Here, the variety of use of the asset is relatively low and service activities can be predicted in advance and standardised (e.g., toner supply, paper supply, maintenance after so many prints etc.). This corresponds with Green et al (2017) who highlights that a G-D and S-D logic orientation are not competing ideals, but instead the conditions within which the organisation is operating would dictate the suitability of each frame through which design is coordinated. Thus, designing for low variety and designing for high variety need not be competing ideals, but instead are suitable for different environments based upon whether they are characterised by continuous change (i.e., high levels of variety) or not. Based on this discussion, it is possible to present the following table:

Main Concepts	Design for Low Variety (A Goods-Dominant Logic Approach)	Design for High Variety (A Service-Dominant Logic Approach)
Value	Created and delivered by the firm. Atomistically embedded within the value proposition. Customer not crucial for value to be created. (Neely, 2008; Baines et al, 2009; Green et al, 2017).	Value is only potential until the customer integrates the resources into their value creating activities. Customer is crucial for value creation and always has to be present. (Smith et al, 2014; Green et al, 2017).
Variety	Low with patterns of use predictable over time. (Ng, 2013).	High, with patterns of use and required functionality uncertain overtime. (Ng & Briscoe, 2012; Green et al, 2017).
Design Emphasis	Organisational changes and the new service activities designed to accommodate complexity	On best positioning the firm to attenuate the variety of use without creating tensions

	post manufacture of the asset. (Baines et al, 2007; 2009; Spring & Araujo, 2017).	between viability, variety and value. Emphasis placed on identifying the appropriate boundary between variety and scalability, with the asset best placed to absorb variety as opposed to human resources. (Ng et al, 2011; Ng & Briscoe, 2012).
Appropriate Design Approach	Product Types – focussed on structural and functional completeness at the point of exchange. (Holmstrom & Partenan, 2014)	Product Instances – focussed on incomplete designs that allow the customer to adapt, and modify equipment in use. (Holmstrom & Partenan, 2014).

Table 4.1. Two types of design approach.

This table builds upon the comparison between the two design approaches outlined in chapter two and provides a more detailed account to compare and contrast which design strategy is more suitable under certain conditions.

4.3.1 Opportunities to explore the phenomenon within servitization

Based on these observations, it provides a number of opportunities to build theory to support our understanding of designing for high variety and resource integration.

First, servitization is a phenomenon which promotes the transition from an exchange based relationship to a longitudinal relationship centred on product service systems and value in use. Whilst value in use and greater customer centricity has been recognised, organisations and scholars adopting a G-D logic lens do not account for the customers' context of use that is characterised by continuous change. In not accounting for the customers' context of use, it is assumed existing design strategies that focus on exchange value and completeness are still valid and therefore used within these contexts. To date, whilst a number of conceptual articles exist, few empirical studies have been emerged in the literature to explore whether designing for low variety is appropriate for environments characterised by continuous change and high levels of contextual variety.

Based on the discussion presented throughout chapters 2 to 4, it is important to address the following research question (RQ1A) to support our understanding as to why designing for high variety has different requirements to designing for low variety:

- What are the limitations of serving high variety whilst using a modularity for low variety frame?

This question forms the basis for sub question 1A.

The S-D logic servitization literature recognises the importance of the customers' context of use in the organisations design activities. In recognising this, a number of scholars have questioned the G-D logic approach of employing existing linear, bounded and sequential design and production methods within the context of servitization. Within these contexts, use of the asset remains exogenous to the organisations service system as they continue to separate design and context (Ng & Briscoe, 2012). Thus, it is assumed the design alone will contribute toward improved viability of the system with respect to operational efficiency and production outputs of the asset. In contrast, the S-D logic literature recognises the role of the customers' context of use and that designs are only valuable to system viability if the customer is able to use them in context to absorb variety and subsequently contribute to an improvement in system viability as defined by the customer. Thus, the organisations design activities should focus on the customers use of the asset and how they can best support the customer in the achievement of their outcomes, which may not be directly related to production outputs (Smith et al, 2014; Green et al, 2017).

The discussion above thus leads to a question as to whether the complexity of the customers' use context, where variety is created, moderates the effect of the design changes made by the organisation on system viability as defined by the customer. Furthermore, with respect to the design changes, it is possible to reflect upon the role of complexity in the assets architecture. Within chapter 2, it was highlighted that functional design changes using traditional manufacturing techniques would potentially increase the complexity of an asset because it was not designed to accommodate the new functionality within said architecture. Based upon this logic, it can be posited that functionality that aligns with existing structural and functional elements would exhibit less complexity when integrated into the architecture but the functionality would align closer to the original design specification and thus may not be significantly different to the resources already available to the customer in use. Based upon this, it is possible to suggest that a functionality further away from the original design specification would result in a higher level of design complexity but would provide the customer with resources significantly different to their existing resources and potentially better suited to their emergent requirements. Given variety means the customers' use context requires new types of resources or functionality to achieve their outcomes, it would suggest the design change complexity could also play a role in the viability of the customers' value creating system. In addressing this issue empirically, it would be possible to inform an organisations design strategy when designing for high variety and the potential limitations of a designing for low variety strategy used in contexts more suited to a designing for high variety strategy.

Based on the discussion presented here and throughout chapters 2 to 4, it is important to address the following research question (RQ1B) to support our understanding as to why designing for high variety has different requirements to designing for low variety:

- Does design change complexity affect system viability greater under a higher use complexity?

This question forms the basis for sub question 1B.

Third, 3D printing is becoming an increasingly popular technology within the field of servitization and designing for high variety for the (re)configuration of resources in use and as an enabler for new service business models. This is especially evident within the context of product centric servitization. Within both academia and practice, it is recognised that 3D printing is more affordable for small to medium lot sizes, with each component in a production run able to be unique in its own right, and that it could allow organisations to focus on resource integration at the point of use so that customers' can modify, tailor and adapt their assets on a mission by mission basis, something that cannot be achieved with traditional manufacturing. Furthermore, 3D printing has been discussed a technology that aligns somewhere in between a purely digital offering and a traditionally manufactured offering. Namely, because 3D printing is primarily driven by software, it allows the organisation or customer to postpone the binding of form and function almost permanently. However, because the end result is a material offering, the level of flexibility in use is not quite as high as offerings that are primarily digital, such as the Apple iPhone. Drawing upon the servitization and design literature, the two suggest that both the customers' use context will become unviable because contextual variety is unable to be absorbed by the physical asset and if the organisation does seek to absorb the variety using the physical asset, a designing for low variety frame would see the asset itself become unviable to manage because it is not designed to accommodate change post production. However, to overcome these challenges, the literature suggests the digital materiality associated with 3D printing could result in lower complexity in both design and use (i.e., variety is absorbed via the constant modification of resources and the delayed binding of form and function) and better support the customers' value creating activities. Furthermore, evidence suggests that 3D printing has a faster response rate to conditions in the environment. Hence, changes and adaptations to a product would be addressed within a shorter time window than otherwise would have been prolonged under a traditional manufacturing design change. It is therefore reasonable to suggest that the number of changes to be made would be increasingly smaller as 3D printing could provide design change interventions at a more frequent interval. In other words, unintended use of the asset and its original design purpose will not escalate to a proportion that is unmanaged before changes can take place. However, this has yet to be explored empirically.

Based on the discussion presented here and throughout chapters 2 to 4, it is important to address the following research question (RQ1C) to support our understanding of why designing for high variety has different requirements to designing for low variety:

- RQ1(C): Does design change complexity affect system viability greater under a higher use complexity post 3D printing implementation as compared to traditional manufacturing?

This question forms the basis for sub question 1C.

Taken together, servitization offers a number of opportunities. First, it provides an opportunity to explore both the limitations and implications of utilising the principles of designing for low variety in a servitized context. Second, it simultaneously provides the opportunity to build theory around the concept of designing for high variety as a process of resource integration. Finally, it provides the opportunity to understand 3D printing an enabling technology for designing for high variety. Furthermore, as discussed in chapter 2, product centric servitization aligns with the scope of this thesis.

4.4 Summary

This chapter has analysed servitization as an appropriate context within which to study designing for high variety. Presently, the literature highlights how organisations currently use existing design theories, tools and methods developed on the understanding that products need to be functionally static, bounded and complete to produce the tangible component of their value proposition prior to its use by the customer. Three reasons for this were identified as their understanding of value, the restrictions of existing manufacturing techniques and that servitized organisations are often using legacy fleets as they transitioned toward being a servitized organisation (Ng & Briscoe, 2012). However, a number of authors have questioned this and suggested new ways of thinking about design from a broader understanding of modularity, value creation, resource integration and S-D logic are needed both within the servitization context and literature more broadly. This aligns with the general discussion of designing for high variety and S-D logic presented within chapters 2 and 3. Whilst questioned, little to no empirical research has been conducted within the domain of servitization and capital goods organisations that shows existing design tools, theories and methods are not suitable for servitized organisations that operate in environments characterised by continuous change and high variety. Furthermore, there is currently little theoretical understanding as to designing for high variety contained within both servitization and the wider literature. Therefore, this chapter has shown servitization as an appropriate context through which to build theory around the concept of designing for high variety and that first empirically examining the limitations of using existing design principles within a servitized context would serve as a foundation for understanding the different requirements of designing for high variety as compared to designing for low variety. Finally, given the profound interest in the use of 3D printing in servitization practice, it provides a novel opportunity to study 3D printing as an enabler for designing for high variety and how the temporary binding of form and function for particular use contexts would help (1) to support the organisation in retaining a low complexity in both the customers' use of the asset, with respect to variety, and (2) to manage the complexity of the physical assets architecture and (3) the assets ability to absorb variety in use, alleviating the need to rely upon human activities to absorb variety.

Chapter 5. Identification of Themes

5.1 Introduction

This chapter analysis and brings together the literature reviewed in chapters 2 through 4 to identify themes central to the phenomenon of interest. These broad themes are then consolidated into seven primary themes that cover both designing for low variety and designing for high variety. The chapter concludes with a brief summary of the chapter.

5.2 Identification and analysis of themes

From the literature of designing for low variety, the following themes were seen as central within the literature. (1) There was a separation between design and context. (2) The purpose of design was to create clear boundaries, a fixed specification of user requirements and a fixed desired outcome of the customer. (3) The purpose of design was to systematically design an offering that can be specified in advance to maximise production efficiency. (4) What happened after the point of exchange was not of interest to the organisation or their design activities and thus freezing of the design requirements into a specification of performance attributes allows organisations to assume contexts are characterised by low variety, even when they are not. (5) Designing for low variety is underpinned by traditional economic thought whereby value is created in exchange. (6) Modularity theory was commonly used throughout the literature and primarily applied within the context of static functional products. (7) The core concepts of modularity were considered to be design rules, architecture, modules, interfaces, interactions and function. (8)

Designing for low variety is not suitable for contexts characterised by continuous changes, where post production design changes are required, because the window for functional re-design is limited.

From the literature of designing for context and S-D logic, the following themes were seen as central within the literature. (1) There is no separation of design and context. (2) Design is an enquiry that evolves over time as actors integrate and engage with resources in their context of use. (3) Designing for high variety requires an organisation to account for five important attributes of use; institutions, actor's agency in context, existing resources in context, system boundaries and the actor's desired outcomes. (4) Designing for high variety is a continual process and supported by the process of resource integration. (5) Designing for high variety has compatibilities with S-D logic and their understanding of value in use and resource integration. (6) A broadened understanding of modularity is compatible with designing for high variety and S-D logic. (7) The core concepts of modularity were considered to be design rules (institutions), modules, module boundaries (interfaces), crossing points (interactions) and architecture (service ecosystem). (8) Digital technology, such as 3D printing, is enabling organisations to serve use through the mobilisation of resources, the unbounded nature of digital materiality and designing for incompleteness.

There are clear disparities between the two design strategies making it possible to distinguish between them. However, from the perspective of both strategies, it is possible to rationalise the list of factors into the following major themes. (1) Resource integration. (2) Design rules. (3) Modules. (4) Actor agency. (5) Variety. (6)

Value proposition design. (6) Technological advances. (7) Value. It is important to note that some terms have different means associated with them depending on what design frame they are tied to. For instance, value proposition design for low variety is seen as a scientific process that requires the complete specification of the design prior to the exchange. In contrast, for designing for high variety it emphasises designing for incompleteness where the boundary between context and design does not exist.

From the servitization literature, the following themes were seen as central to the literature and thus making it a suitable context through which to study the phenomenon of interest. (1) Servitization is a phenomenon that promotes the transition from an exchange based relationship to a longitudinal relationship centred on product service systems and value in context. (2) Scholars within the S-D logic community agree that existing principles of designing for low variety are not applicable within contexts characterised by high variety and continuous change. (3) The design of the physical asset may be contributing to the service paradox because organisations utilise a design for low variety frame when trying to serve use. (5) The physical asset is best placed to absorb contextual variety and to do so requires a greater level of digital materiality to be exhibited from the asset. (6) Servitization provides an opportunity for scholars to better their understanding of designing for high variety by understanding the limitations of designing for low variety when used in a context focussed on use and outcomes.

5.3 Summary

This chapter has identified a number of themes that have emerged throughout the course of the literature review contained within chapters 2 to 4. Whilst the themes for design were identified according to each design frame, they were then consolidated to seven broader themes that cover both designing frames. These themes will form the basis of the empirical chapters as it allows the author to be guided by a tentative list of themes and categories that guide the researcher during data analysis (Voss et al, 2002).

Chapter 6. Literature Review Summary, Knowledge Gaps and Justification of Empirical Studies

6.1 Introduction

This chapter summarises the vast analysis of the literature that took place in chapters 2 to 5 and sets out the primary gaps in knowledge, research objectives and the primary research questions that this thesis seeks to address. Finally, this chapter concludes with a justification of the three, theory building empirical studies that are conducted within this thesis.

6.2 Summary of literature

The basic definition of design that was used to initiate this research was that it is a conceptual activity that specifies the structural and functional elements of a design prior to the production of the asset. Thus, design is a conceptual activity that bridges the research and development activities of an organisation and their production activities. It was found that design from this perspective focussed on complete functional assets that could be specified in advance. Furthermore, it was found that design was underpinned by a scientific approach to design that was grounded in reductionism and value in exchange that emphasised the separation of design and context. This design frame was then illustrated using existing knowledge surrounding modularity theory and its role in product and service design. It was found that modularity conformed to these design principles and specified that the complete functional and structural elements of the product be specified in advance of production. In focussing on the specification of a complete product in advance of its use, modularity was found to conform to the other general principles of designing for low variety outlined in this review. Finally, by specifying the functional boundaries in advance of its production, it was found it severely limits the organisations ability to accommodate design changes because the window to re-design and integrate functional attributes has been closed once the offering has been produced. The primary reason behind this was the limitations of traditional manufacturing techniques and the inability to retain complexity within the existing modules of the architecture because interfaces for the new functionality did not exist prior to post-production design changes. Therefore, modularity for low variety was conceptualised as not being suitable for contexts characterised by continuous change and high variety.

Following this basic understanding of design, it was found that a new phenomenon of interest was emerging within both the literature and practice; designing for high variety. Within this frame, design was underpinned by incompleteness and an understanding that value is derived in use. In following this understanding of value, it highlighted that use is characterised by continuous change and that existing design strategies may not be suitable within these contexts. Instead, designing for high variety found compatibilities with S-D logic where emphasis was placed on resource integration, value in use and the constant readjustment of resources (designs) in context to satisfy the desired outcomes of the focal beneficiary. This highlighted that design and context are intimately entangled and this has implications for the organisations design activities. Namely, focussing on value in use and the entanglement of design and context, the organisations design activities will need to account for institutions, actors' agency in context, existing resources in context, system boundaries (the context) and the desired outcomes in use. Three examples of designing for high variety were subsequently provided and these highlighted a key enabling factor in being able to design for high variety; digital technology. The outcome of the literature review found that designing for high variety was converging on understanding design as a process of resource integration, supported by the affordances of digital technology, that emphasise value as created in use and experience.

In acknowledging compatibilities between designing for high variety and S-D logic, it was important to review the S-D logic literature before converging on the consensus that it could provide suitable insight into the process of resource integration and designing for high variety. However, it was found that the theoretical underpinnings of resource integration were lacking. This prompted analysis of the existing theoretical underpinnings with modularity theory as discussed by Baldwin (2008), Ng (2013) and Hartmann et al (2018) seen as a suitable theoretical frame for understanding designing for high variety as a process of resource integration. Furthermore, adopting modularity theory provided three major benefits. First, whilst S-D logic has largely focussed on institutional theory for resource integration, modularity theory encapsulates institutions as design rules and thus aligns with existing S-D logic thought by encapsulating existing thinking in a broader understanding of resource integration for the purpose of designing for high variety. Second, it retained a level of compatibility with existing research in the design community providing a platform from which to build upon. Third, Spring &

Araujo (2009) identified the creation of thin crossing points as a primary objective of OM in the design of processes. This led to modularity in a designing for high variety frame being labelled as modularity in context to distinguish it from modularity for low variety.

Thus far, the differences between designing for high variety and low variety have been identified, modularity theory has been proposed as a relevant theoretical frame though which to understand the phenomenon and S-D logic had been identified as an appropriate lens through which to study the phenomenon. Throughout the literature review, it was found that servitization was discussed on a number of occasions with respect to both design frames. This led to the conclusion that servitized organisations, primarily characterised by product-centric servitization, would be a suitable context to conduct this study. The primary reasons behind this were: (1) servitization emphasised the shift from value in exchange to value in use where the customers' context of use was of primary focus. (2) S-D logic scholars had found servitized organisations are utilising principles of designing for low variety to design the material component of their value proposition and that this was not suitable for servitized contexts, characterised by high variety and continuous change, and may be contributing toward the service paradox because post-production design changes make it difficult for organisations to manage the complexity of their assets architecture over time. (3) The literature review found servitization required new, multi-dimensional ways of thinking about the physical asset and its ability to absorb variety at the point of use with advances in digital technology, such as 3D printing, fuelling this debate. Taken together, servitization is seen as a novel context within which to address the overarching research question and three sub research questions.

Finally, chapter 5 converged on a number of broad themes derived from the literature review. First, it presented a number of key themes for each design frame and two contexts of servitization before converging on seven broader themes that encapsulated those identified for each design frame. These themes will subsequently be used to guide the data collection and analysis phases so that the author is provisional guided to what they are looking for within the data.

6.3 Knowledge gaps and research objectives

The main bodies of literature analysed through chapters 2 to 5 have been examined in detail. The previous section provided a summary of that examination and it had to the following four research gaps:

1. There is no established conceptual model representing designing for high variety as a process of resource integration.
2. Empirical evidence to show why designing for low variety is not suitable for contexts characterised by continuous change and high variety has not yet been provided.
3. The existing literature offers limited insights as to why designing for high variety has different requirements to designing for low variety. In not providing significant insights into the differences, the literature fails to provide guidance as to the design decisions that organisations need to take.

These gaps provide the basis for the following research objectives:

- To understand the differences between designing for low variety and designing for high variety in a servitized context.

The objective of the study is researched using a theory-building approach. To satisfy the objective, the thesis addresses the following primary research question:

- Why does designing for high variety have different requirements to designing for low variety?

In order to sufficiently address this question, the literature review identified three sub research questions that will help to address the overarching research question via three empirical studies. These questions are:

- RQ1(A): What are the limitations of serving high variety whilst using a modularity for low variety frame?
- RQ1(B): Does design change complexity affect system viability greater under a higher use complexity?
- RQ1(C): Does design change complexity affect system viability greater under a higher use complexity post 3D printing implementation as compared to traditional manufacturing?

The following section justifies the theory building approach of this thesis. In doing so, it further highlights the gaps in knowledge and justifies both the research objective and research questions.

6.4 Justification of a theory building approach

The literature review has demonstrated a lack of theory with respect to resource integration and designing for high variety. Whilst modularity theory, as conceptualised by Baldwin (2008), helps to envisage resource integration from a broader perspective, it has been developed within the designing for low variety frame. This limits our ability to adequately support and understand designing for high variety as a process of resource integration where design and context are intimately entangled. This is a gap in both the modularity and S-D logic literature.

In finding compatibilities with S-D logic, it is assumed that it could inform an organisations design strategy through a greater understanding of the process of resource integration and value in use and in doing so, potentially advance or replace existing theories that have so far been identified as providing insight into designing for high variety. However, it is noted that theoretical contributions in this field are currently limited. Within the literature, both conceptual and qualitative studies have been conducted with respect to designing for high variety. First, the conceptual articles, whilst they discussed theoretical considerations, did not add a considerable amount of knowledge to be able to fully appreciate the dynamics of designing for high variety. For example, Ng (2013) provided a number of illustrations highlighting the importance of modularity theory, but she herself called on the community to adequately theorise and empirical explore modularity from a S-D logic perspective so that we can fully understand and appreciate how to design for high variety. Second, whilst a small number of qualitative articles exist, they have not empirically explored the phenomenon from the perspective of modularity theory. For example, whilst Holmstrom & Partanen (2014) discuss designing for high variety through a focus on product instances, they do so from the perspective of Brian Arthurs (2009) combinatorial evolution theory to highlight and explain how technology is enabling such practices. Thus, there is a need to conduct empirical studies with respect to modularity and resource integration in order to inform our understanding of designing for high variety.

It is reasonable to posit that designing for high variety, its relationship with modularity and how understanding design from the perspective of resource integration can allow firms to focus on serving high variety contexts is still relatively unclear within the literature. Thus, whilst insight has been gleaned, the answer to why does designing for high variety have different requirements to low variety remains fundamentally unanswered. This gap needs to be filled in order to determine whether designing for high variety has fundamentally different requirements to designing for low variety and if it does, how organisations can design their operations to allow them to adopt such a design approach. For this reason, this thesis conducts three exploratory, theory building studies that seek to fill this gap and address the research question presented in section 6.3.

6.5 Summary

This chapter has provided an in-depth analysis of the literature review, identified the knowledge gaps and formulated a number of research objectives and research questions. In performing this analysis and highlighting these gaps, the justification for performing three, theory building studies was provided. It has made the case for moving towards an understanding of design as a process of modular resource integration in at least four ways. First, the literature has shown that in understanding value as phenomenologically determined in use, existing design strategies that focus on functional attributes of products and the separation of design and context are not suitable for contexts characterised by continual change and high variety. Second, value creation as determined by the beneficiary in use has been shown to be a dynamic and emergent process, emphasising the need to understand design as an adaptive process of resource integration as determined by the focal beneficiary and supported by the organisation(s). Third, modularity theory has been identified by a number of scholars as providing a theoretical foundation for understanding design as a process of resource integration, but little theoretical or empirical insight has to yet to be provided within this area. Finally, digital technology allows resources to be mobilised across time and space allowing them to be integrated into the customers' context of use to adapt, modify and tailor offerings so they are bespoke for individual contexts of use.

The following chapter introduces the philosophical underpinnings of this research, justifies the selection of a single case study research design, presents the major data collection techniques and addresses any validity, reliability and ethical issues associated with the research.

Chapter 7. Philosophical Underpinnings and Case Study Research Design

7.1 Introduction

The previous chapters reviewed the literature concluding with the knowledge gaps, research objectives and research questions. This chapter discusses and justifies the research methodology and aims to provide clarity that the philosophical underpinnings and research design are appropriate for this research.

The main purpose of this chapter is to justify the philosophical stance, research design and the specific data collection techniques employed within this thesis. As illustrated in figure 7.1, the research onion illustrates the spectrum of research methodology from philosophical underpinnings to methodological techniques that have to be taken into account when conducting a research project. Saunders et al (2003) recommend that the items within each layer are addressed one by one, from embracing a research paradigm through to identifying the appropriate procedures and techniques for data collection and analysis at the centre of the onion.

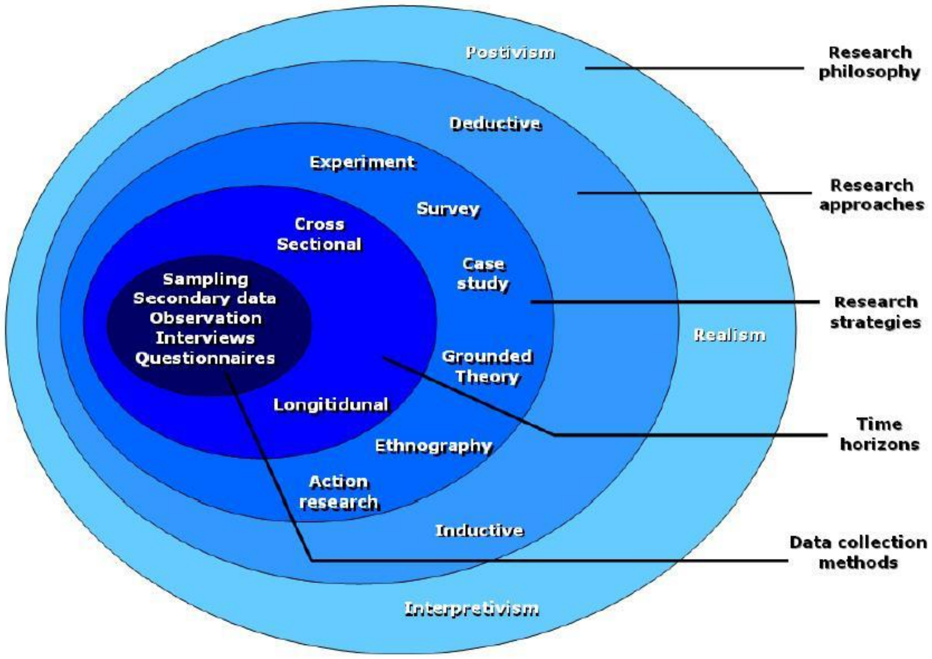

Figure 7.1. The research onion (Saunders et al, 2003).

The rest of this chapter is divided into five sections. First, section 7.2 introduces and justifies the choice of critical realism within this thesis. Second, section 7.3 discusses research methodology and design. Third, section 7.4 presents and justifies the appropriateness of a case study research design before introducing the case organisation. Second, section 7.5 pays particular attention to the data collection techniques used during this research. Section 7.6 discusses the measures taken to address validity and reliability issues relevant to the research. Finally, section 7.7 concludes the chapter with a discussion of ethical considerations.

7.2 Research philosophy: critical realism

Saunders et al (2003) suggest that underpinning the research within a suitable philosophical paradigm is an important starting point as the epistemological and ontological assumptions of the chosen paradigm determine which techniques for data collection and analysis are appropriate. A paradigm refers to a worldview that is underpinned by a basic set of assumptions and beliefs typically shared by the research community (Guba and Lincoln, 1994). Ontology refers to the assumptions held by the researcher relating to the nature of reality whilst epistemology refers to the relationship between the researcher and their understanding of knowledge and reality, generally asking the question how we know what we know (Bryman and Bell, 2011).

The following section introduces critical realism before justifying its use within this thesis.

7.2.1 Discussion of critical realism

Critical realism combines transcendental realism (natural sciences) with critical naturalism (social sciences) in order to generate a philosophical paradigm that creates a suitable interface between the social and natural worlds (Johnson & Duberley, 2000). Bhaskar (1989; 2008) makes a distinction between the intransitive objects of scientific enquiry that exist independently of human knowledge and the transitive dimension that is socially constructed and allows humans to make sense of the world within which they live. For critical realism, there is a reality independent of us, but our knowledge of it is it always socially constructed. Thus, critical realism argues against reducing reality to only observable events and switches the focus to the generative (causal) mechanisms that enable the emergence of these events that can then be empirically observed (Danermark, 2002). This perspective therefore refutes the positivist epistemology in that only objects that are observable can be regarded as knowledge (Johnson & Duberley, 2000). However, it does defend causal explanation in that identifying mechanisms as causal factors that create observable events and behaviours. To show these mechanisms, critical realism employs a 'retroductive' argument. Retroduction is when a researcher moves from superficial appearances to generate knowledge of the structures that cannot be observed (Johnson & Duberley, 2000).

At the heart of critical realism is relativism. In developing critical realism, Bhaskar accepts one of the principles of relativism (epistemic) but rejects the other (judgemental). Critical realism accepts that different realities can be created by individuals, with one interpretation being no better than the next when compared with one another. That is, critical realism accepts the tenets of epistemic realism and acknowledges that knowledge may be the outcome of social construction. However, judgmental relativism is rejected based on the fact that it does not allow for an informed evaluation of science and second, judgemental relativism states that it is possible to make a choice between two competing theories.

A further important point that distinguishes critical realism from positivism and interpretivism is that it acknowledges the role of actors. That is, actors generate knowledge via social constructions created as a result of their active interaction with an external reality. This concept separates critical realism from positivism and interpretivism by:

1) Recognizing that mechanisms that may exist within an external reality can be influenced by human agency (separating it from positivism); and

2) External reality can constrain or facilitate human action (separating it from interpretivism).

This is important for this thesis as it has been acknowledged that actor agency in context is an important factor organisations need to account for in designing for high variety.

The following two sections discuss the ontological and epistemological assumptions of critical realism.

7.2.1.1 Critical realism and ontology

Critical realism places emphasis on ontology as opposed to epistemology. It adopts a stratified ontology that is divided into three distinct 'domains of being' (Bhaskar, 1989). These domains are represented as the real, actual and empirical domains. The real is made up of the generative mechanisms and causal structures that are created by the generative mechanisms, which together create the actual events that occur in the world (Bhaskar, 1989). The 'real' domain is not necessarily observable but whose generative mechanisms activate causal powers that subsequently create the events that exist in the 'actual' domain. The actual domain is said to both consist of and represent all of the potential events that could be created by the generative mechanisms and their causal structures. Below these two domains, exists the empirical domain, where actors can actually experience and/or observe phenomenon. This means that to understand the generative mechanisms causal powers is a core goal for critical realism and science more generally (Rotaru et al, 2014). Following this logic, critical realism sees observation as fallible (Easton,

2010) and means that criticality is an important dimension of critical realism. Being able to see the same data via a different theoretical lens can help gain a greater understanding of the real world that can be empirically observed (Woodside and Wilson, 2003). Therefore, whilst critical realism believes in an objective reality, there will always be a number of competing theories to explain said reality (Mingers, 2000). Finally, because theories are fallible and changeable, they must always be tested according to an objective reality (Mingers, 2000) in order to generate the most accurate and suitable understanding of the world, both social and natural (Hunt, 1990). This means the social sciences are able to reflect and refine their theories and knowledge about the world over time, assuming their claims are historical and contingent.

7.2.1.2 Critical realism and epistemology

Epistemology within critical realism is influenced by its ontological assumptions. Namely the understanding that there are real, actual and empirical domains of being. The influence of these domains is that knowledge of something is not necessarily the same as the thing itself. This means individuals cannot define something (e.g., laws and mechanisms) only by what they perceive because they exist independently of the individual observing the phenomenon. This results in an understanding that reality, existing independently of us, may not be possible to perceive. Hence, a number of theories can be used to explain the same phenomenon.

Within the remit of this thesis, the implication of this epistemological view is that each participant is given the full opportunity to discuss and explain their understanding of reality without judgement. This is particularly important for this thesis because individuals from different functional disciplines, where their view of reality may be different to both individuals in their own discipline and outside of it, are interviewed within the qualitative studies. Following the cautious approach to epistemology outlined by critical realism, where caution is taken because reality may or may not be possible to perceive, this thesis recognises that individuals have their own views and that these are their perceptions of said reality and therefore are only partial perceptions and one possible way of explaining reality.

Importantly, the ontological and epistemological assumptions of critical realism influence the methodological decision making. The assumptions highlighted in the two previous sections allude to a methodological flexibility. According to Easton (2010), critical realism's ontological and epistemological assumptions are tolerant to different methodological approaches. Critical realism deems methods to be suitable if it is relevant to the phenomenon that is being studied and what the researcher wishes to learn about a given phenomenon (Easton, 2010; Bryman & Bell, 2011). This suggests critical realism is methodologically flexible, making it particularly suited to case study research (Easton, 2010) such as the one conducted within this study where a number of different methods are used.

7.2.1.3 Critical realism and operations management

Within OM, two studies have explored the applicability of critical realism paying particular attention to the role of human agency (Aastrup & Haldórsson, 2008; Rotaru et al, 2014). Inherent in positivism and rationalist based research is the idea of a 'closed system'. However, Aastrup & Haldórsson (2008) argue that this limits OM research as closed systems research assumes the social structure, and within that human agency, is inferior to the material aspects of the logistics chain. Furthermore, acknowledging closed systems are limited aligns with propositions put forward within critical realism. Bhaskar (2008) highlights that predicatability is only possible in closed systems where mechanisms constantly produce the same result. However, in open systems, where there are multiple things effecting the outcome, means it is difficult to hold things constant and so the same result cannot be guaranteed. This is especially appropriate for this thesis given both actor agency and emergence are key properties of use that means value co-creation cannot be predicted over time. This is highlighted by Peters et al (2014) who highlight resources may not hold the same value when used again, even if the desired outcome is the same. Aligning with these assumptions, Aastrup & Haldórsson (2008) therefore suggest that critical realism is more appropriate for OM and logistics research as it accounts for the structures and human agency that is embedded in material circumstances.

7.2.2 Justification of critical realism

Based on the above discussions, critical realism has been deemed appropriate based on a number of factors that allow the researcher to appropriately address the research questions and objectives. These are discussed below.

First, the use of a retroductive approach is deemed suitable for this study as it combines both inductive and deduction logics in order to help understand and improve our knowledge of structures and mechanisms that underpin the events and behaviours associated with the phenomenon of interest. This is particularly suited to this research given it is a case based, theory building study that seeks to improve our theoretical understanding of modular resource integration and how this can help organisations design for high variety as opposed to low variety. Whilst modularity has primarily been discussed within engineering and design literature, the broader view adopted by this thesis that encompasses human agency and institutions that may not may not be possible to perceive by individuals. Thus, a critical realist stratified ontology aligns with a S-D logic understanding of institutions that may be present in the real domain that cannot be directly observed, but the mechanisms influence the actual and empirical domains that are possible to perceive. Within OM, Rotaru et al (2014) found that this retroductive approach helps to facilitate the development of theory as it helps to emphasise the role uncertainty plays in the study of complex processes and systems. Given the focus of this thesis is on the complex process of resource integration where actor agency and emergence make resource requirements for value creation uncertain and difficult to predict, a retroductive approach is seen as both suitable and desirable.

Second, and related to the above, critical realism is flexible toward the use of different methodological approaches. This is particularly important for this study as it uses a number of different methods to gain insight into the phenomenon. Whilst the literature does advocate that mixed methods is suitable for all paradigms, critical realism appears most suited to the use of mixed methodologies assuming the relevance of the chosen methods can be adequately justified as appropriate for the phenomenon being studied.

Finally, critical realism aligns with a central component of this thesis, S-D logic. Within critical realism, actors and objects are not considered explicable if they are not located within the context of their structures and interactions (Johnson & Duberley, 2000). This aligns with the S-D logic understanding of value co-creation as phenomenologically determined during use and within the confines of the service ecosystem and institutional structures that govern resource integration and actor behaviour. This is reflected in critical realism's acceptance of the role of human agency and that individual actors may evaluate their experiences differently to each other and even to themselves when evaluated within another context. In addition, critical realism acknowledges that causal mechanisms may exist in external realities and these can effect and be affected by individual actors and their agency (Johnson & Duberley, 2000). This understanding aligns with earlier S-D logic work surrounding service systems and more recently, research that discusses service ecosystems and institutional arrangements (Taillard et al, 2016; Vargo and Lusch, 2016). Therefore, in both S-D logic and critical realism, the notion of exchange, value creation and resource integration are context dependent and contingent upon enabling or constraining structures.

Introducing and justifying the philosophical paradigm prior to a discussion of the research design and data collection techniques followed the advice of Guba & Lincoln (1994) and Saunders et al (2003). As this research has justified the application of critical realism as the philosophical underpinning for this thesis, the following section will now discuss the research methodology, design and data collection techniques in more detail.

7.3 Research design and methodology

Following justification of critical realism, this section focusses on the choices surrounding research design and methodology. It begins with a discussion of methods historically used within OM.

7.3.1 Operations management, research philosophy and research methods

The previous sections discussed the three main paradigms within business and management research. This section pays particular attention to their applications within OM and in particular the growing consensus that empirical science is required to keep OM theory relevant.

Established scholars in the OM community propose the dominant debate in OM is rationalism vs empirical science (Meredith, 1998) with the latter increasing in popularity in recent decades in order to advance theory and ensure the field remains relevant to practice (Craighead and Meredith, 2008).

Rationalism is linked to deduction and analytical approaches that primarily use quantitative methods. This approach is strongly associated to positivism as it seeks to formalise theory through deduction and hypothesis testing (Bryman and Bell, 2011). A further characteristic of the rationalist approach is that observations are considered independent of the theory that is used to explain them, thus allowing the researcher to study, manipulate and control the phenomenon at will (Meredith, 1998). In contrast, empirical science relates to knowledge generation that can be verified via observation or experiment and is guided by theory and/or practice (Gupta et al, 2006).

Research related to operations was seen to be dominated by analytical methods and rationalism more generally as the most common approach to the study of operations was mathematical modelling and simulations (McCutheon and Meredith, 1993). In 1998, Wacker presented findings that showed analytical research methods accounted for 81.8% of research in OM during the period 1991-1998. However, whilst analytical, deductive methods dominated OM, considerable criticism of this approach has mounted. It is important to note however, that during this period operations research (OR) and OM were largely discussed as a single body of knowledge, both researching various areas of operations. Whilst both related to operations, the relationship between has been made clearer in recent years, with OR being the field most commonly associated with mathematical modelling and a rationalist approach to operations research and decision making.

That said, it is important to recognise some of the criticisms associated with a rationalist approach. The primary criticism within leading OM journals was that rationalist approach lacked relevance to real world problems and did little to develop powerful theory (Meredith, 1998). This led to concerns that OM theory risked becoming irrelevant to practicing managers (Meredith, 1998). For instance, Shubik (1987) stated the science of management research required more than mathematical models and analytical techniques that did not account for the context within which the phenomenon was located. Furthermore, mathematical models and other analytical techniques do little to account for existing theories (Shubik, 1987). Flynn et al (1990) question whether rationalism is suitable for overcoming the academia-industry divide. However, they do acknowledge that OM and OR have strengths in analytical techniques and these can be complemented if first grounded in rich, detailed empirical studies that seek to build an understanding of the phenomenon. Bailey (1992) highlights that rationalist approaches using statistical techniques on objective measures are likely to be trivial at best. In addition, the researcher has difficulty in explaining anomalies or information that goes beyond their model of interest when using purely analytical techniques. McCutheon and Meredith (1993) highlight how the rationalist approach is not appropriate for studying successful practitioner led OM developments, such as Just-in-Time, whereas other research strategies such as case study research, underpinned by empirical science, can. Meredith (1998) states that the rationalist approach finds it impossible to cope with the variations associated with real-world phenomenon, limiting its relevance to practice. Gupta et al (2006) found positivist driven research was not suitable for the study of complex, ever changing business environments.

Finally, Roth and Menor (2007) stopped short of criticising analytical methods in OM, but suggested the nature of services required different research techniques to study SOM that did not rely on analytical methods.

Following these criticisms, a push toward empirical science ensued (Meredith, 1998). In a review of the literature, Godsell et al (2010) found a change in the type of research being conducted within operations and supply chain management research between the years 1991-1995 and 2004-2008. The use of analytical techniques dropped from the earlier period to the most recent by 13%, whilst empirical research articles increased by 8.4% in their sample of seven leading OM journals. Gupta et al (2006) found empirical articles were the most commonly used in Production and Operations Management (POM) during the period 1992-2005. With specific reference to SOM, Machuca et al (2007) found empirical studies in OM journals (the study does not include operational research and management science journals) accounted for 46.2% of all articles between 1997-2002. These articles highlight the increasing use and relevance of empirical science, as opposed to the positivist driven approach of rationalism in OM and the advantages that can be obtained when combining the two approaches (Flynn et al, 1990). It is however, worth noting that many of these studies remove OR from their analysis and without OR, the evidence suggests OM has always been accepting of empirical science. That said, it is still evident that an increase in empirical science occurred whilst the use of rationalist approaches reduced.

In summary, operations, both OR and OM, has traditionally been dominated by rationalist approaches. However, leading OM scholars recognised the academic-practitioner divide was largely driven by current techniques that did not adequately represent practice and lacked the ability to produce strong theory. Since then, empirical science has gained popularity as a suitable approach to the study of real-world problems. With specific reference to servitization, much of the work produced has been in the form of empirical science primarily utilising a case study research design. Thus, OM has seen a shift from a purely positivist, analytically driven community toward a more open community that recognises the limitations of analytical approaches and the benefits of empirical science for theory generation in OM.

This section has shown how OM, whilst always interested in empirical science, is becoming increasingly interested in qualitative, theory building case studies that seek to maintain the relevance of OM by grounding it in practice. Furthermore, a case study research design is a suitable design for exploring phenomenon from a critical realist perspective (Easton, 2010). Based upon this, the following section discusses the case study research design and its suitability to this research.

7.4 Case study research design

A case study is a research strategy that seeks to understand the dynamics of a particular phenomenon within single or multiple settings (Eisenhardt, 1989) and is particularly useful when the phenomenon is difficult to separate out from its natural setting (Benbasat et al, 1987; Yin, 1993). McCutheon and Meredith (1993) state that case study research is the best way to ensure constraints and conditions of real-world phenomenon are represented accurately. A further benefit of case study research is the ability to answer 'why' questions through the use of rich descriptions of the phenomenon (Yin, 2003). Of particular relevance to this research its philosophical underpinnings is that a case study research design is methodologically flexible and is designed based upon the research objectives (i.e., theory building or theory testing). This was brought to the fore by Voss et al (2002) who present a number of different case research designs.

Within this thesis, three studies are conducted to understand why designing for high variety has different requirements to designing for low variety and in doing so, builds theory that underpins modular resource integration and its role in designing for high variety. In following an iterative cycle that moves between theory and data multiple times between the three studies, it allowed the thesis to establish logical reasoning for the causal relations between the variables derived from the qualitative studies (Gibbert et al, 2008). Finally, theory building from cases increases the likelihood of producing novel theory (Eisenhart, 1989). Upon evaluation of the above and given the novel access to data that this thesis has, a single case study was therefore deemed suitable for this research for the following reasons:

- Case studies are particularly suited to answering why questions and thus suits the research question presented in this thesis;
- Case studies are methodologically flexible based upon the purpose of the study and this aligns with a critical realist stance on methodological decisions;
- It was not possible to remove the phenomena from its natural setting;

- The case study provided the researcher with uncommon research access;
- Rich data can be sought from the organisation to help generate an in-depth understanding of what is being studied;
- The organisation provides an opportunity to utilise quantitative data that is based on actual management practice (Flynn et al, 1990); and
- The primary purpose of this research is to build theory of which case study research designs are particularly well suited.

The following section introduces the case organisation.

7.4.1 The case organisation

The case organisation is the land division of BAE Systems Plc. They are one of the world's largest defence contractors and offer a diverse range of military vehicles, who in recent years have looked toward servitization to differentiate themselves and retain their competitive edge. To date, they have provided availability of platforms, availability of parts and spares and repairs service contracts for their customer (principally the UK MoD), with the latter two services being the most common. During war time, the equipment-in-use with the customer is likely to be (re)configured on a consistent basis to accommodate the changing nature of their context and to fill a capability gap that is preventing the customer from achieving their outcomes. Therefore, one of the primary roles of the organisation during war time is to support the customer in use by designing resources that satisfy emergent needs. During war time, the organisation can therefore be seen as designing for high variety. The (re)configuration of the physical assets is done via a process called urgent operational requirements (UOR). An UOR is a process used by the UK MoD during UK military campaigns when there is a requirement for military goods or services that arise from:

1) Identification of capability gaps currently not filled or emerging as a result of current operational use; or
2) Where existing orders need speeding up to cope with the increasing demands or emergent requirements during operational use in order to bring the capability required into service at a faster rate[6].

Within this thesis, the UOR process has been selected as the primary case study as the phenomenon of interest within the research is 'transparently observable' (Pettigrew, 1988) and provides the researcher with an opportunity for uncommon research access (Yin, 2003). It is important to note that a case organisation is not a case study. The case study is a particular phenomenon studied within an organisation. In this thesis, the case organisation is the land division of BAE Systems Plc and the case study is the UOR process that was followed during the recent UK military campaigns in Iraq and Afghanistan. In particular, the UOR process is broken into two parts to form an embedded case study. First, the architecture of the asset is investigated to gain insight into the effect unexpected design changes have on the products architecture. Second, the use of the asset before and after the change is analysed to understand whether design changes absorb variety in use and

[6] UK MoD UOR information can be found here: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/528625/DSPCR_Chapter_09_UOR_Procurement_Jun_16_Edn.pdf

support the customer in the achievement of their outcomes (co-creation in context). These two aspects of the UOR process form two sub units of analysis, making it an embedded case study (Yin, 2003).

The following table provides an overview of the case organisation.

Case Organisation	BAE Systems Plc – Land Division
Main Offerings	Armoured Fighting Vehicles, Armoured Personal Carriers, Main Battle Tanks, Engineering Support Vehicles, Amphibious Combat Vehicles, Ammunition, Precision Munitions, Artillery Systems, Missile Launchers.
Number of Vehicles in Service	4000+
Primary Purpose	To design, manufacture, upgrade and support their offerings whilst in service.
Procedures for Responding to Emergent Needs	Urgent Operational Requirements
UORs processed	200+
Number of Staff Employed	≈ 1600

Table 7.1. Overview of BAE Systems Plc – Land Division.

As discussed above, the particular case studied was the UORs required during the UKs military campaign in Afghanistan and Iraq during the period 2001-2014. Specifically, three of the organisation's vehicles were chosen for this study as they were subject to a number of UORs during the two military campaigns discussed. Furthermore, they have been in service for over thirty years, have been deployed in environments for which they were not originally designed and they were designed under the designing for low variety frame. Thus, according to the literature review within this thesis, they are not suited to the contexts within which they found themselves in (i.e., those characterised by continuous change and where emphasis is placed on resource (re)configuration to support use and outcomes). This provides an opportunity to study both why the designing for low variety frame is not suitable for contexts characterised by continuous change and why designing for high variety has different requirements to designing for low variety within the context of the UOR process within two specific war zones. In each of the studies, the two main parts of the embedded case are addressed. These two aspects include (1) the architecture of the asset before and after each design change and (2) the customers' context of use before and after each design change. These are developed further in the context of each study in chapters 8, 9 and 10. The three vehicles used within the study are shown in the following figures in their pre and post Afghanistan and Iraq states.

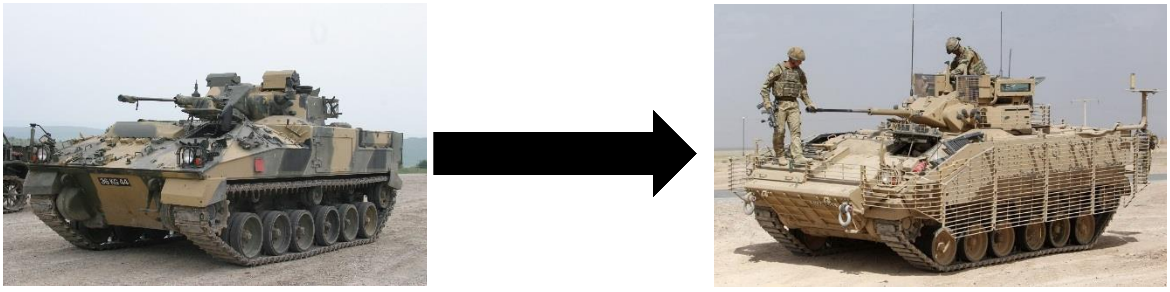

Figure 7.2. BAE Systems Warrior pre (left) and post (right) the Afghanistan and Iraq campaigns[7].

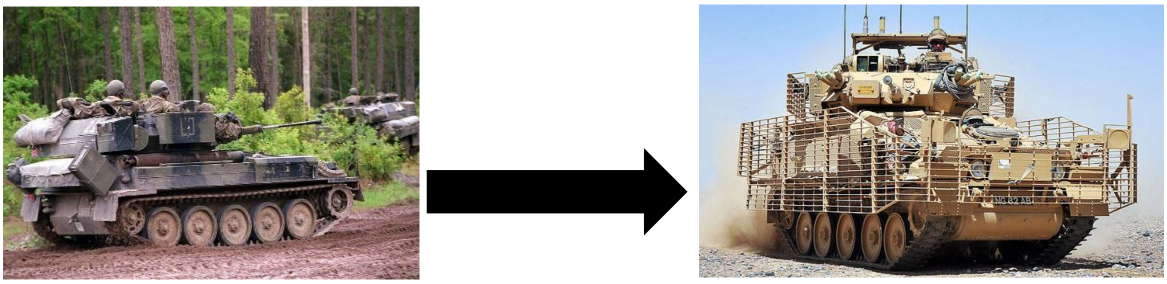

Figure 7.3. BAE Systems CVR(T) pre (left) and post (right) the Afghanistan and Iraq campaigns.

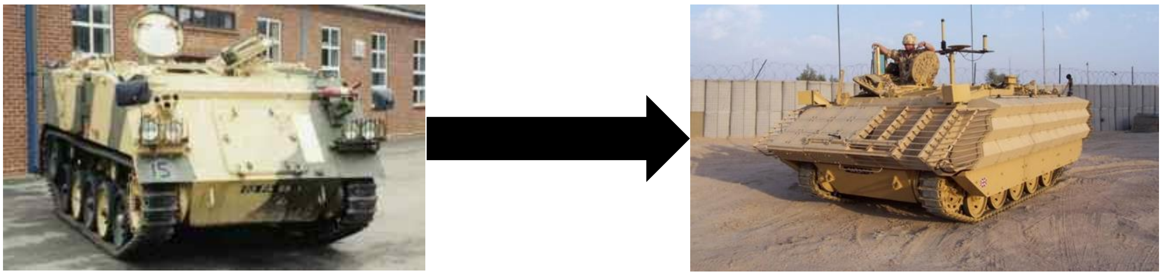

Figure 7.4. BAE Systems Bulldog pre (left) and post (right) the Iraq campaign.

The vehicles were already tied to a range of service contracts, such as spares and repairs contracts, but the UOR process added additional service activities revolving around design consultancy and in some cases, manufacturing of components.

[7] The images used in figures 4.2, 4.3 and 4.4 have been extracted from google images and can be found using the following search terms: 'BAE Systems Warrior'; 'BAE Systems CVR(T)'; 'BAE Systems Bulldog'. Credit is given to the copyright holders of these images.

However, manufacturing was usually outsourced to another organisation as specified by the MoD.

Moving forward, the organisation, in part driven by the customer, are investigating whether technology such as 3D printing can be used for resource (re)configuration and the creation of bespoke components on a mission-by-mission basis. This is representative of pursuing a product instance and incomplete product approach that emphasises designing for high variety. This form of value proposition would potentially form part of the organisations servitization strategy in the future. Furthermore, there is recognition that during wartime, which cannot be predicted when the vehicle is originally designed, vehicles will be subject to environments, threats and more generally different use contexts than those they were designed for. This results in a UOR being raised and functional design changes post-production of the asset taking place. Thus, this serves as an example of an organisation having to design for high variety and integrate resources to maximise resource density even after the product has been designed, produced and exchanged with the customer. However, as highlighted in the literature review, the organisation is using legacy vehicles that were designed for low variety as opposed to use and this may have repercussions for the organisation when satisfying UORs. As the organisation transitions toward higher level servitization contracts such as availability of platforms and outcome-based contracts and integrates 3D printing for resource (re)configuration into their portfolio, UORs are likely to become more common place and so it is important to understand the different requirements of designing for high variety and designing for low variety if they are to successfully design for high variety.

This case highlights a number of similarities between research and practice. First, both the literature and practice acknowledge the servitization transition. Second, they both highlight how organisations continue to use existing manufacturing techniques, tools and theories (designing for low variety) even when the context they are serving is characterised by constant change and high variety (where the UOR process represents high variety . Finally, both academia and practice recognise the enabling role of digital technologies in designing for high variety. Thus, this case aligns with the primary objective of this research and provides a novel case through which to develop theory for designing for high variety as a process of resource integration.

7.5 Data collection procedure

The data collection framework used to guide the data collection is presented in figure 7.5. The following subsections discuss each element of the framework in more detail. It is important to note that whilst the framework presents a linear, sequential process, it was a continuous process of iteration that meant the researcher went back and to between data collection and data analysis. This iterative cycle is common within case study research and often advocated to allow a continuous cycle whereby the research alternates between comparing and contrasting the data with existing literature (Glaser and Strauss, 1967).

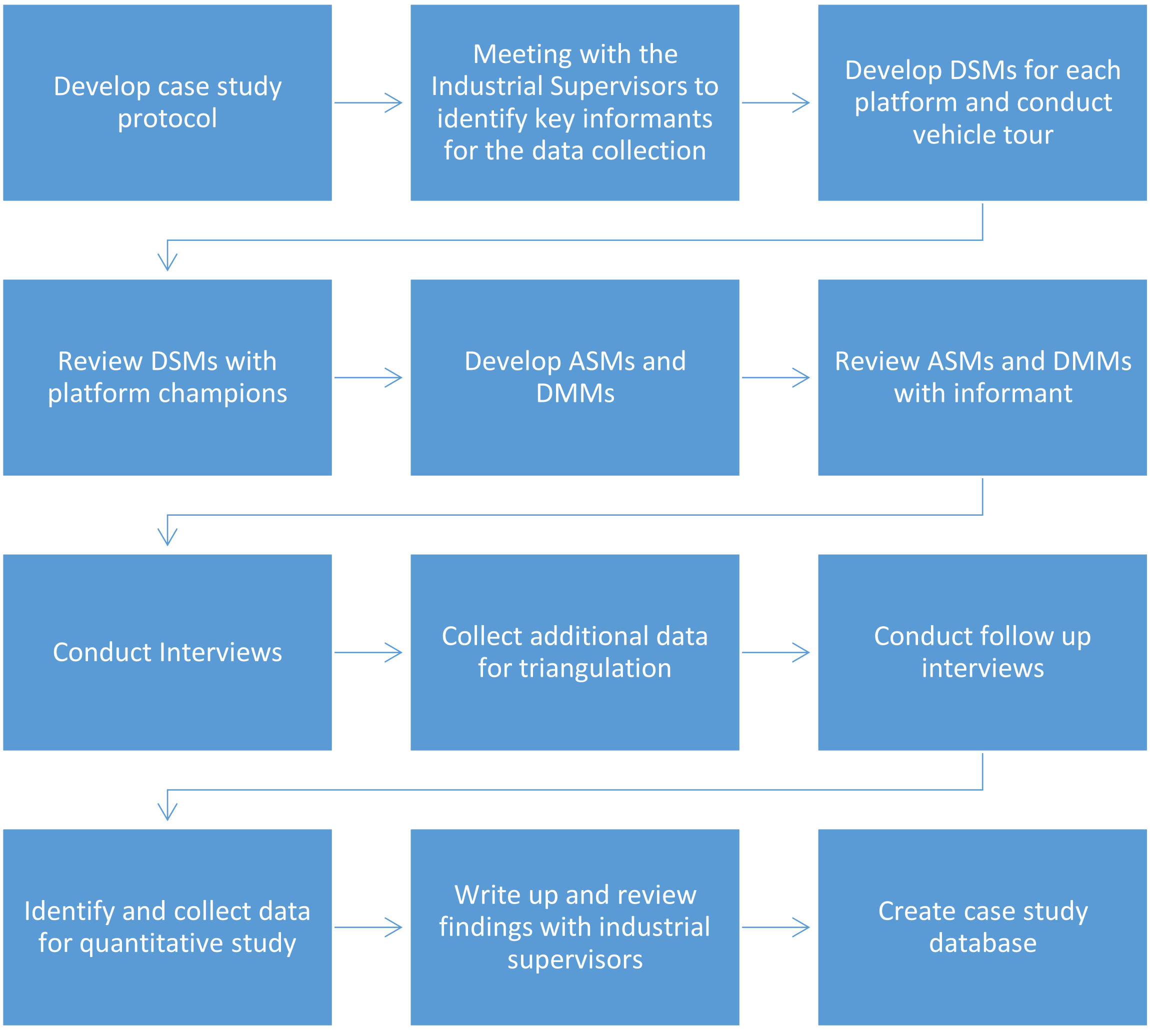

Figure 7.5. Data collection framework.

In line with Benbasat et al (1987), this thesis explicitly reports the data collection and data analysis techniques (see empirical chapters for data analysis techniques) in order to enhance confidence in the results and the relationships that were identified between the variables.

1. Develop Case Study Protocol.

A core component of case study research is the development of a case study protocol (Voss et al, 2002; Yin, 2003). Within case study research, the case study protocol is a method used to enhance the reliability of the research as it outlines the details of key attributes used to guide the research. Some of these items include the measurement instrument (interview questions) and research variables. The case study protocol is also used as a guide for the research during the data collection. Finally, the case study protocol allows other researchers to understand how the data collection was conducted (Yin, 2003).

2. Meeting with the Industrial Supervisors to identify key informants for the interviews.

An initial meeting with the industrial supervisors (project champions) was held to outline the work to date and identify suitable individuals for each stage of data collection. These stages included construction of the static platform Design Structure Matrices (DSMs), the Activity Structure Matrices (ASMS), the Domain Mapping Matrices (DMMs), semi-structured interviews and documentation analysis.

Following the advice of Eisenhardt and Graebner (2007), this thesis sought to identify multiple respondents from different functional disciplines within the organisation in order to avoid subjectivity and bias. Jick (1979) states multiple viewpoints increases the accuracy of the data and subsequent results. Seeking multiple respondents also meant any inconsistency or conflicting information could be cross checked in order to resolve any potential issues (Voss et al, 2002).

Key informants for the vehicle DSMs, ASMs and DMMs were identified in order to facilitate the subsequent stages of data collection. As this research utilises data from three platforms, three individuals were sought from different platform teams to support the construction of the static platform DSMs. Identification of experts for DSM construction is advocated by Yassine (2004). These individuals were labelled ‘platform champions’. The platform champions were the platform managers for each vehicle.

Key informants were also required for the ASMs and DMMs. The platform champions were deemed not suitable by the researcher, the industrial supervisors and the platform champions themselves for this stage given their insufficient knowledge and expertise of military campaigns or that they were not in the business during the time of the Afghanistan and Iraq campaign. Subsequently, the industrial supervisors identified two members of staff at the main BAE Systems Plc branch and a team of field service representatives (FSR) who operated within close proximity of the customer.

Next, the researcher and industrial supervisors identified 29 Interviewees to be interviewed over two phases. Interviews were arranged and conducted with a wide range of different job functions as shown in table 7.4. The 29 interviewees were selected as they were all knowledgeable of, or experienced in the UOR process from either a design or service perspective. To complement the organisations knowledge, a respondent from the field service representatives was also selected as they had knowledge of the customers’ context of use and experience of Iraq and Afghanistan campaigns that were being studied within this thesis. Managerial level participants were selected for the follow-up interviewees as they were identified as having both a broader and more detailed knowledge of the UOR process and in particular, the design of the assets and potential use of technology going forward. Having more informed informants for the second stage was important as the first round allowed some questions to be added, tailored and modified in order to derive the detailed and suitable responses from the managerial level respondents.

Participant Position	**Number of Interviewees**
Technology Lead	1
Head of Availability Services	1
Technical Programme Manager	1
Platform Manager	3
Field Service Representative Manager	1
Service Representatives	5

Engineers	17
Strategy Executive and Principle Technologist	1

Table 7.2. Interviewee information.

3. Develop the DSMs for each vehicle and conduct vehicle tour.

Initial meetings were held with each platform champion to discuss the research, the rationale behind the research, the DSM approach and the type data required for each DSM. This helped build trust between the researcher and informants prior to any data collection and made it possible for certain material to be handed over prior to the construction of the DSMs (Voss et al, 2002). Furthermore, the meeting helped establish whether the data available was sufficient for the unit of analysis of this study. The discussions with each platform champion clarified data could be provided at a module level for analysis at the subsystem level. This was seen as suitable for this research based on the literature review and previous architectural and modularity studies (e.g., Mikkola, 2003) and the type of organisation the case organisation was i.e., a prime systems integrator.

Following the meeting, a number of steps were taken to develop and finalise the vehicle DSMs. These steps are listed below:

- A presentation was given to the researcher about armoured vehicle design and general module interactions with examples given based on the three platforms being utilised within the study as well as future armoured vehicle designs;

- A table of all components was emailed to the researcher and included a breakdown of which components belonged to the initial vehicle architecture and the subsequent UOR design changes;
- A vehicle tour was conducted where each vehicle was studied by the researcher and discussed with a member of staff to understand the UOR changes and module interactions;
- The researcher constructed each base DSM (the first variant of the architecture without any UOR design changes) and asked the platform champion to confirm the components and interactions were correct.
- Following confirmation, the researcher constructed the DSM for each UOR design change and again asked the platform champion to confirm the interactions in each DSM were correct.

1) Decomposing the system into its component level;
2) Identifying and mapping the interdependencies/interactions between the components within the matrix; and
3) Rearranging the units so as to establish the modules within the architectures as outlined by the platform managers (Pimmler and Eppinger, 1994; Browning, 2001).

The final step would usually focus on identifying the most appropriate modular solution for any given product/service that is new. However, as this is a retrospective case where the architecture had already been agreed upon and the product manufactured, this step focussed on arranging the DSM into the format the platform currently existed, as opposed to seeking the optimal design solution as per new product development studies.

4. Review DSMs with platform champions.

Following construction of the DSMs, the researcher arranged one final meeting with the platform champion for each vehicle. The review was used to discuss any unknowns, have the DSMs checked for accuracy and check they were representative of the vehicle architectures from the original specification right through to the final UOR design change. At the end of the review, each DSM was signed off by the platform champion.

5. Develop ASMs and DMMs.

An initial meeting was held with the two informants within BAE Systems Plc to discuss the research and what data would be required for the construction of the ASMs and DMMs. ASMs can be seen as an extension of the DSM, with the major difference being what it is modelling. Both use the square matrix to represent interactions, but for the ASM the interactions are between activities within a system or process as opposed to components/modules/subsystems of a physical product. Commonly, ASM's, like TSM (Task structure matrix) are used to model design processes to identify and reconfigure iterations and feedback cycles between different activities within the matrix (Baldwin & Clark, 2000; Eppinger & Browning, 2012). They are often seen as representing the same thing, and this is reflected in a design structure matrix handbook, where Eppinger & Browning (2012) highlight how process architectures are often called ASMs or TSMs. The major difference appears to be the field they are used in, with the strategy literature often using the term TSM (e.g., Baldwin & Clark, 2000) and the engineering design and operations management literature commonly using ASMs (e.g., Browning, 2001).

The ASMs sought to clarify the activities conducted by the customer, using the case organisations assets, between leaving the compound (i.e., the army base) and returning to the compound (i.e., the army base after they have finished the mission). The customers' context of use or customer 'space' therefore refers to the customers' use of the asset during combat fighting missions. This is a slightly different use of ASMs, where ASMs are traditionally used to model design activities that are internal to the organisation and inform the conceptual design decisions before the product or service is transferred to the operations function to create and deliver said design. Modelling the design activities allows the organisation to reflect on the organisation of the design teams and modify the design process to reduce feedback cycles and improve the efficiency of the whole process. However, this thesis seeks to model the customers use of the asset and understand whether design changes are able to support more efficient and effective use of the asset when the context of use changes. Thus, activities here are simply distinct portions of the customers' value creating activities between the defined start point (leaving the compound) and the defined end-point (returning to the compound). Modifying these activities was not the purpose of this activity but ASMs provided suitable information and visualisation deemed to suitably represent the activities pre and post integration of the design changes to support the purpose of this study.

After the ASMs were modelled, the DMMs were then used to map the interactions between people (i.e., soldiers) during the activities and the different components of the vehicles contained within the DSM. These two informants were chosen as they had previously served in a particular capacity (role cannot be stated for anonymity) within the conflict zones. They were therefore deemed to have sufficient knowledge of the customers' context of use and the effect both the threats and the UORs to counter the threats had on the customers' context of use.

It is important to note that this was an open but structured discussion as opposed to an interview, which is why these informants are not part of table 7.2. These open but structured discussions are referred to as 'meetings' and were deemed more suitable for this portion of the data collection as it provided a much more focussed setting for the creation of detailed ASMs and DMMs.

Following the meeting, a number of steps were taken to develop and finalise the ASMs and DMMs. These steps are listed below:

- A second meeting was held to discuss the ASMs. This step involved the researcher and two informants openly discussing the Afghanistan and Iraq campaigns, the reasons behind the UORs and a standard mission profile that could be converted into distinct activities. In addition, sequencing was discussed to establish interdependencies between activities and the functionality of the vehicles.

- Following the meeting, the ASMs and DMMs were constructed. These were then presented to the two informants via email, who clarified whether they were accurate and representative of the activities and interactions during a standard mission.
- A final meeting was held with a number of FSRs to finalise the DMMs given their close proximity to the customer. During the meeting, a few changes were made before the DMMs were finalised as accurate at the end of the meeting.

During each of these stages, extensive notes were taken to facilitate the construction of the ASMs and DMMs.

6. Conduct Interviews.

Following the identification of the interviewees with the industrial supervisors, semi-structured interviews lasting between 15 and 60 minutes were conducted. For this research, only a single investigator conducted the interviews.

Generally, the interviews started with general questions that sought to understand their role within the company and what their exposure, experience and understanding of ALM technology is to date.

At various points during the interview, the interviewer would probe the interviewee further on their answers in order to gain further insight into an interesting or novel response that they have provided.

All interviews were recorded and transcribed verbatim and accompanied by extensive notes that were taken during the interviews.

Following the interviews, the researcher asked each interviewer if they could be contacted with any additional questions in the near future. All interviewees agreed to this via email and provided their contact details.

7. Collect Documents and other data for triangulation.

To add validity to the research, documents were collected in order to triangulate the data. Triangulation is understood to be the use and combination of methods to study the same phenomenon (Denzin, 2012). Triangulation improves the accuracy of the results and the reliability of the data whilst also allowing for the use of multiple data sources that may uncover data that may not have been included elsewhere (Denzin, 2012), creating a more complete picture of the phenomenon. Table 7.5 shows the different sources of data collected as well as highlighting other factors, such as type of data.

Source of Data	Type of Data	Collected during
Semi-structured interviews	Primary, qualitative data.	Phase 7 and 9
DSMs and process models	Primary, objective data.	Phase 3 and 5

MoD documents	Secondary public documents (text)	Phase 7
Defence Standard documents	Secondary public documents (text)	Phase 7
Media Publications	Secondary public documents (text)	Phase 7
Ross Kemp in Afghanistan season 1 and 2	Secondary public documents (video)	Phase 5 and 7
Our war: Afghanistan. BBC documentary	Secondary public documents (video)	Phase 5 and 7

Table 7.3. Data source and type used to triangulate the data.

The documentary data sources listed in table 7.4 were also used during the construction of the ASMs and DMMs in phase 5. Whilst the documents were primarily collected during phase 8, the documentary was collected and watched earlier to help inform the ASMs and DMMs. The justification for their inclusion is that these documentaries provided an insight into the customers' context of use during the UK's Afghanistan campaign.

8. Conduct follow up interviews.

Follow-up interviews were conducted with more senior members of staff. This allowed missing and additional information to be obtained as well as focus more on the UOR process and designing for high variety. These follow up interviews consisted of six interviews with senior management from both the engineering and service business units.

9. Identify and collect data for the quantitative studies

Following completion of study one, the researcher sought to identify and collect data relevant for the quantitative study contained within chapter 9. All data collected was tabulated within an Excel spreadsheet and stored within the case study database.

Data collection was informed by the findings from study one and the conceptual development of the constructs and associated measures in study two. The data was sought from a variety of sources.

First, data for the design change complexity construct was collected from the static platform DSMs.

Second, data for use complexity construct was collected from the ASMs.

Third, performance data was collected from multiple sources and cross validated to ensure accuracy. These sources are listed within appendix 1.

More detail as to this step is provided in chapter 10.

10. Write up and present to industrial supervisors

Detailed reports were created in the form of PowerPoint presentations as requested by the industrial supervisors. These were created to highlight and summarise both the progress to date and key findings from the data collection into a concise form that could be distributed orally and visually during a presentation. This also presented an opportunity to receive feedback from the industrial supervisors. Feedback allowed slight modifications and refinements to be made that influenced the next stages of the research.

Reviewing the case study reports, DSMs, ASMs and DMMs with the industrial supervisors allowed the researcher to verify the findings, refine some of the identified constructs and variables and triangulate the findings further.

11. Create case study database.

The final step of data collection was to create a database of all of the data collected. All of the data from the steps outlined above were integrated into a single database, making it easier to organise, document and manage the data that was collected (Yin, 2003). Creating a case study database is recommended within the literature in order to enhance the reliability of case study research (Voss et al, 2002).

7.6 Validity and Reliability of the Research

This section presents the validity and reliability aspects of the research. Specifically, it presents the measures taken to ensure high quality research was conducted. A criticism of case study research is that it lacks the methodological rigor of other methodologies, such as surveys (Stuart et al, 2002). However, this section seeks to highlight how a valid and reliable study was conducted to ensure trustworthy results were obtained.

This research addresses the issues of face validity, construct validity, internal validity, external validity and reliability (Bryman and Bell, 2011). However, as this research is mixed-methods, there is extensive use of qualitative techniques, in particular during the first study. The measures of validity and reliability mentioned above are traditionally associated with quantitative research (Bryman and Bell, 2011). Voss et al (2002) suggests that whilst their use within case study research has generally been accepted, other measures for qualitative research have been put forward; confirmability, credibility, transferability and dependability (Bryman and Bell, 2011; Miles et al, 2014). Taking these into consideration, this thesis also pays attention to these four alternate approaches to validity and reliability.

7.6.1 Construct Validity and Confirmability

Construct validity refers to how well the operationalised construct reflect what it is they are supposed to measure (Gilbert et al, 2008). Bryman and Bell (2011) state that confirmability corresponds to construct validity in qualitative research and deals with the issue of the researcher avoiding their own values and beliefs intruding upon the research process and outcomes.

This research addresses these issues in two ways:

- Producing a clear chain of events; and

- Data triangulation (Gilbert et al, 2008).

First, the research aimed to establish and record a chain of evidence so that the reader can understand how the researcher went from the research questions to the conclusions. The chain of evidence aims to provide clear evidence as to how the key parts of the research were derived and the process through which the conclusions were drawn (Yin, 2003). The structure, process and information provided within this thesis makes it possible to work both forward from the research questions to the conclusions and backward from the conclusions to the research questions.

Second, data triangulation was a core component of this thesis. Data triangulation ensured the accuracy and robustness of the data through continuous cross validation of results through the use of different data sources that focus on the same phenomenon of enquiry (Denzin, 2012). Furthermore, using multiple sources in theory building research helps build construct validity as definitions and methods of measurement emerge during the analysis (Eisenhardt and Graebner, 2007).

Third, meetings with the industrial supervisors and iterative data collection cycles with key informants allowed for validation and refinement of the DSMs, ASMs and findings more generally.

It is important to note that for the quantitative study in chapter 9, this research only claims face validity as it remains an exploratory, theory building study. As the sample size is relatively small, and some of the constructs within the framework are new, the purpose of the study is to show that they 'look like they work' as opposed to 'have been shown to work' (Bryman and Bell, 2011).

7.6.2 Internal Validity and Credibility

Internal validity relates to causality and causal relations between the concepts being studied (Gibbert et al, 2008). Credibility parallels internal validity and purports to reflect how believable the findings are (Bryman and Bell, 2011).

Gibbert et al (2008) proposes three techniques to enhance internal validity in case study research. These are:

- Creation of a clear conceptual framework;
- Pattern matching;
- Triangulation through multiple sources.

First, a clear conceptual framework and both definitions and justifications of the constructs and their relationships were provided (see chapter 9). This included logical reasoning that clearly shows how the conclusions were drawn (Gibbert et al, 2008). This framework discusses why the independent variable leads to the dependent variable and how the relationship is moderated by a further variable, as opposed to the effect being caused by a spurious variable not represented within the framework (Gibbert et al, 2008). Second, a high degree of triangulation was employed throughout the research by complimenting the semi-structured interviews with additional data sources. Pattern matching, to a certain degree, does occur during the discussion stage, but was not actively pursued in this research. In addition, explicit reporting of the data collection techniques and presenting logical reasoning as to how the relationships between variables have been derived enhances confidence in the results and internal validity (Benbasat et al, 1987).

Finally, credibility was addressed through regular meetings, feedback sessions, email exchanges and update meetings with the two industrial supervisors and other key stakeholders. These techniques occurred throughout the duration of the research and allowed the researcher to gain valuable feedback, identify any missing data and uncover any weaknesses within the research.

7.6.3 External Validity and Transferability

External validity refers to how representative the findings are beyond the context within which they were generated (Bryman and Bell, 2011).

As this study is a single organisation, it has limitations in that it is difficult to generalise the conclusions beyond the case organisation within which the study was conducted (Voss et al, 2002). Furthermore, Eishardt and Graebner (2007) suggest the use of four to ten cases is ideal for enhancing the generalizability of case study research, numbers this study does not achieve.

However, analytical generalizability is used throughout this thesis to compare the emerging theory with existing theory and frameworks (Yin, 2003). This technique does not permit comparison across other settings, but seeks to generalise the findings against other established theories and frameworks. This approach is in stark contrast to statistical generalizability which seeks to generalise beyond the sample used to the general population (Gibbert et al, 2008). Finally, a number of research propositions were also generated for the research community to use in theory testing studies in the future (Eisenhardt and Graebner, 2007).

7.6.4 Reliability and Dependability

Reliability reflects the ability of another researcher to replicate the study and produce the same results (Yin, 1993). This parallels with dependability which refers to whether or not the findings will apply at other times (Bryman and Bell, 2011).

Voss et al (2002) puts forward that implementing two simple techniques can help enhance the reliability of case study research. These techniques are:

- Creation of a case study protocol; and
- Creation of a case study database.

Both of these techniques were used within this research during the data collection phase.

First, a case study protocol was created prior to data collection and was used throughout the study (see appendix 2). Second, all data that was collected was put into a case study database in an accessible and manageable manner.

These two techniques enhance reliability by creating transparency in the research process (Gibbert et al, 2008).

7.7 Ethical Considerations

This final section discusses the ethical considerations this project has accounted for in both study one and study two. This research combined steps outlined by Bell and Bryman (2007) and Bryman and Bell (2011) to ensure this research conformed to all necessary ethical considerations. Though the authors put forward ten steps, only seven steps were deemed necessary for this research. These are:

- Ensuring no harm would come to participants;
- Ensure there is evidence of informed consent;
- Ensure no methods of deception are used;
- Ensure the participants understand the mutual benefit of the research;
- Ensure the participants are aware of the affiliation;
- Ensure confidentiality of the collected data and;
- Protect the anonymity of the individuals and the organisation.

First of all, the study was submitted to the Biomedical and Scientific Research Ethics Committee (BSREC) based at Warwick University. The ethics board signed off the study and confirmed it posed little to no risk to participants (see appendix 3). Furthermore, the point of contact within the company also approved the study.

Secondly, all participants read the information pack approved by the BSREC and signed the consent form that was provided before the interviews began (see appendix 3). This ensured they knew what they would be interviewed about, data storage procedures and that the company would only have access to anonymous interview transcripts, maintaining the anonymity of the participants.

Thirdly, the participants were made aware that this research was jointly funded by the Engineering and Physical Science Research Council (EPSRC) and BAE Systems Plc. This made it clear that the research was of direct benefit to the company who wished to explore and understand future uses of ALM as it was funded directly by them.

Finally, the company was happy to be named. However, within the contract between the University and the sponsoring company, it was agreed that the case company would review any outputs of this work before they were made public. This was put in place given certain sensitivities surrounding defence work and provided the firm with reassurance that any published works resulting from this research did not release any confidential information.

Having discussed in detail the methodological elements of this research, the next chapter presents the first study.

Chapter 8: Study One: The Limitations of the Modularity for Low Variety in a High Variety Context

8.1 Introduction

This chapter describes the first study. The data analysis procedure presented within the following empirical chapters relied upon the case study protocol (see appendix 2) and this study sought to address the research objective and question (specifically RQ1(A)) presented in chapter 6.

The objective of the data analysis presented within this chapter was to allow the theory to emerge from the data in order to answer part of the research question. Only part because the context of this study is the limitations of modularity for low variety in high variety contexts. Combined with study three, a complete picture of the phenomenon will be provided. The analysis contained within this chapter is driven by the themes presented within chapter 5. This allowed the researcher to focus their attention on specific data during the analysis (Voss et al, 2002).

The context of this study is in exploring the limitations of using a modularity for low variety approach within a context characterised by high variety. Here, the case organisation has deployed the three vehicles used within this case study to Iraq and Afghanistan where the UK military are conducting combat missions. These vehicles were originally designing for a different context of use and were designed using a modularity for low variety frame. This gives the opportunity to explore the limitations of this approach in a context characterised by continuous change and high variety and address RQ1A presented in chapter 6 and section 8.2.1 in the next section.

This chapter is divided into four sections. First, section 8.2 presents the research objectives, research question, the unit of analysis and the data analysis procedure of this study in detail. Second, section 8.3 presents the findings from the analysis. Third, section 8.4 presents the discussion of the findings before a brief summary is provided in section 8.5.

8.2 Qualitative data analysis

This section presents the research question, research objectives, the unit of analysis and the data analysis procedure for this study.

8.2.1 Research questions and objective for study one

In chapter six, the research objective (RO) and research question (RQ) were presented. These were:

- RO: To understand the differences between designing for low variety and designing for high variety in a servitized context.
- RQ: Why does designing for high variety have different requirements to designing for low variety?

In order to address the overarching research objective and question, this study addresses the following sub research question:

- What are the limitations of serving high variety whilst using a modularity for low variety frame?

8.2.2 Unit of analysis

As described in chapter 7 (see section 7.3.1), the case is the process of urgent operational requirements (UORs).

The unit of analysis has two sub units of analysis and thus represents an embedded case study design (Yin, 2003). First, the architecture of the physical asset before and after each UOR design change is the first sub unit of analysis. Second, the activities that take place within the customers' use space form the second sub unit of analysis.

In the context of modularity theory, interactions between components of the system can be studied from a whole system (e.g., the vehicle), sub system (e.g., powertrain, weapons system), module (e.g., engine, turret) and component (e.g., nuts, bolts and side plates) level (Mikkola, 2003). As described in chapter 7, it was agreed with the platform champions that breaking the system down to modules to allow analysis to occur at a subsystem level was the most suitable level of analysis given the organisations' role as a systems integrator. Analysis as the subsystem level is for the first unit of analysis; product architecture pre and post UOR.

In line with Eppinger & Browning (2012), activities are defined as the elements of action that comprise a process. These can include tasks, decisions or information gathering. Within the context of this thesis, activities were examined from the perspective of the customer using the offering and the boundary was created between leaving the main compound to returning to the compound (i.e., from the start of a mission where the asset is used, to the end of a mission when they stop using the asset). Between these two points, activities were broken down into discrete portions of the mission where new tasks or decisions had to be made and the use of the asset between these discrete portions would or could change. By defining activities as tasks or decisions, it accommodated the primary purpose of this study, to understand the use of the asset by the customer and how this helps organization's design for high variety for which the asset is exposed to during its use. This unit of analysis for activities was agreed upon by the participants of the study who had firsthand experience of the Iraq and Afghanistan campaigns. Analysis of these activities is for the second unit of analysis; the customers' context of use pre and post UOR implementation (the design change).

In summary, the unit of analysis is each design change of the physical asset as driven by the customers' use of the offering and is made up of two sub unit of analysis, that collectively form a complete picture of the customers' context of use with respect to the designing for high variety and the UOR process that reconfigures the organisations assets to respond to emergent changes in the customers' context of use.

8.2.3 Data analysis procedure

This section describes how the data was condensed and displayed in order to facilitate the data analysis. To do this, this thesis followed the general three step procedure presented by Miles et al (2014). Whilst discussed as distinct, it important to note that each of the three stages are entangled during the data analysis phase. The three steps include data condensation, data display and drawing and verifying conclusions. First, data condensation required the researcher to select, simplify and transform all of the available data. Second, data display involved sorting the data into an organised assembly of information that allowed the research to draw and verify conclusions. Finally, conclusion drawing required the researcher to constantly draw conclusions throughout the analysis process before drawing final conclusions and verifying them at the end of the process.

Specifically, the analysis employed within this section is twofold. First, a growth gradient analysis is conducted in accordance with guidelines provided by Miles et al (2014). The purpose of the growth gradient analysis is to derive a *'display that illustrates the amounts, levels or qualities of change across time through the use of points and links accompanied with text'* (Miles et al, 2014, pp. 198). The growth gradient analysis pays particular attention to the variables associated with changes to the customers context of use and the assets architecture (i.e., post design changes/resource (re)configuration) that were tentatively derived from the extant literature. The purpose of using these variables for the growth gradient analysis is to generate a greater understanding of both the rate of change for different variables and relationships amongst them as they vary over time, both pre and post design change.

The growth gradient analysis is further supplemented by a thematic analysis (Flick, 2006) of the interviews, documents, documentaries and field notes to provide a greater understanding of the phenomenon and provide insight into areas the growth gradient analysis could not.

The following section describes how the data was documented and coded.

8.2.3.1 Documenting and coding matrix data

For the growth gradient analysis, the data first needed to be documented and displayed in an appropriate format before the graphs could be produced. First, the three types of matrices (design structure matrix (DSM), activity structure matrix (ASM) and domain mapping matrix (DMM)) needed to be tabulated and displayed in a specific matrix format before information could be extracted and placed into an excel spreadsheet ready for the growth gradient analysis. The matrices were created using the steps presented in section 7.5. Developing the matrices to visualise the effect of the design changes on the assets architecture and the activities and interactions within the focal beneficiaries' context of use was an important part of the theory building process. As discussed within chapter 2, 3 and 4, the customers' context of use, or service ecosystems more generally, was made up of the physical asset, customer practices, existing customer resources and environmental factors, all of which interact with one another during use (Ng & Nurudupati, 2010). Constructing detailed models using DSMs, ASMs and DMMs allowed relevant and detailed information to be displayed consistently across all cases. DSMs can be seen as matrices that represent the 'architecture' of a system or product whilst the ASMs can be regarded as models that represent the structure and interactions of a process and the activities contained within that process

(Eppinger and Browning, 2012). Both the DSM and ASM are subsequently combined to create a DMM representing the interactions between the activities in the customers' context of use and the physical assets components (i.e., activities vs. components matrix). Thus, the DSM visualises the first component of the unit of analysis (asset architecture), the ASMs visualise the second components of the unit of analysis (the customers' context of use) and together, the DMM visualises the entire context of use (the use of the asset within the customers' use space).

The main elements of the matrices and their definitions are provided in table 8.1.

Design Structure Matrix Elements	Definition
Product Architecture	Arrangement of components within a product that interact in order to perform a specific function. The architecture is the totality of the components and the relationships amongst them.
Components	Elements that comprise the product/system. Components can be defined at different levels of analysis (Mikkola, 2003).
Interactions	The connections and relationships between components within a product/system. Interactions can be of different types, with process interactions regarded as input-output relationships between activities.

Cluster	A set of components grouped together because of their high interactivity. Usually a cluster represents a module or subsystem that perform a specific function within the product architecture.
Process	A system of activities and resources arranged in order to transform inputs into outputs to satisfy the requirement of the focal beneficiary.
Process Architecture	The structure of a process containing within it a number of activities and the interactions and feedback loops between these activities.
Activities	The elements of action comprising a process e.g., tasks, decisions, information gathering.
Sequencing	Is an analysis technique for activities structure matrices that focusses on logically ordering activities to identify parallel, sequential and coupled activities.
Domain	The realm or type of matrices representing a specific product/system i.e., ASM, DSM or organisational structure matrix.
Domain Mapping Matrix	A non-square matrix mapping interactions

	between one type of matrices (e.g., a DSM) and another (e.g., an ASM).

Table 8.1. Design structure matrix methodology and definitions (adapted from Eppinger and Browning, 2012).

In total, six core sets of DSMs, ASMs and DMMs were produced (one for each platform variant). Within these core sets, further matrices were produced each time a design change occurred within the physical assets architecture. See appendix 4 for matrices associated with each platform.

Given the nature of the matrices, the condensing and displaying of data was interwoven into the data collection procedure, meaning they took place at the same time. The process through which they were collected, condensed and displayed as matrices can be found in section 7.5.

For the growth gradient analysis to take place following the creation of the matrices, additional data displays needed to be created from the information contained within them and within emails between the participant and platform champions. This data was coded and tabulated within an excel spreadsheet according to variables associated with the themes identified within chapter 6. Coding with respect to research questions, objectives and themes is important for case study research as it provides a theoretical base for the coding to be grounded upon (McCutheon and Meredith, 1993; Voss et al, 2002). Specifically, the data contained within the emails was organised into the following variable headings that were found to be associated with the theme value proposition design and variety (contextual) (see table 8.2):

- what the design change was;
- what platform the change occurred to;
- When was the design change requested;
- When was the design change implemented;

The data contained within the matrices was organised into the following variables:

- The number of activities before a change took place (ASMs);
- The number of activities after a change took place (ASMs);
- The total number of interactions within the architecture before a change (DSM);
- The total number of interactions within the architecture after a change (DSM);
- The total number of interactions inside a module before a change (DSM);
- The total number of interactions inside a module after a change (DSM);
- The total number of interactions outside a module before a change (DSM);
- The total number of interactions outside a module after a change (DSM);

All of the data discussed above was tabulated within an excel spreadsheet and stored within the case study database.

Following data tabulation, condensation and organisation, it was possible to conduct the growth gradient analysis. Within this analysis, the variables were defined in terms of growth as it is anticipated that all variables will either increase (grow) or decrease (shrink) in terms of quantities (amounts/frequency) over time following each design change. By mapping multiple variables onto a single growth gradient chart, it is possible to derive insight into interesting interrelationships between the variables and in some cases, it is possible to identify causation factors at work (Miles et al, 2014). It is important to note that whilst causation factors may emerge, this study remains exploratory.

For the analysis, the X axis is allocated to time in years, constrained to the years 2001-2014 (in line with the years the UK military were in Afghanistan, the longer of the two campaigns). The Y axis has been allocated numerical values between 0 and 160 to indicate frequency of change and was dictated by the maximum value present within the excel spreadsheet. In total, there are six growth gradient outputs; one for each variant of the vehicles. The researcher has attached various critical events to the line, including what design change was implemented, what it was designed to counter and key events of the conflicts, in order to facilitate an understanding of the movements of the variables depicted in the analysis. This information was derived from emails, field notes and documentary data.

The output of the growth gradient analysis is presented in section 8.3 and appendix 5.

8.2.3.2 Documenting and code interview, field note, document and documentary data

This section describes the process of documenting and coding the text and video based data used within this study. First, the recorded interview data was transcribed verbatim. Interviews were recorded because it was deemed important that the researcher had exactly what people said during the interview and to ensure all data was recorded accurately and not lost during data display and condensation. The decision was also driven by the fact that the industrial supervisors advised the researcher that access to participants of this kind was highly unlikely to be repeated. Field notes made during the interview process and during visits to the sites were typed up as soon as possible after the visits in order to maximise information recall and accurately depict information. Each transcript was briefly analysed and compiled into a PowerPoint presentation to discuss with the industrial supervisors. Other written documentation, such as government documents, were kept in original form for coding and analysis. Video data, such as documentaries, were viewed a minimum of twice, and summarised for coding and analysis.

When conflicting information between the different sources of data became apparent (i.e., when interview data, documentation and documentary data did not match), either the respondent or the industrial supervisors were sought for clarification and conflict resolution. However, should neither be able to resolve the conflict, they were asked to identify an individual who can help resolve the conflicts identified. By identifying a number of different respondents during this process allowed for data triangulation (Voss et al, 2002). Once accurate information was confirmed, the author presented the information to the industrial supervisors before moving to the next stage. This meant the interview, field notes, documentation and documentary analysis were presented to or be discussed with the industrial supervisors before the final report was produced. Report in this case refers to the findings and discussion presented within the empirical chapters of this thesis.

To code and analyse the data associated with this section of analysis, this thesis employed a thematic analysis (Flick, 2006). Thematic analysis is a flexible, qualitative analysis technique that identifies, analyses and reports themes within a given set of data (Braun and Clark, 2006). Importantly, thematic analysis is compatible with a critical realist stance as it is theoretical and epistemological flexible (Braun and Clark, 2006) whereas other techniques, such as interpretive phenomenological analysis, are tied to a specific epistemology, such as a phenomenological epistemology. In line with Braun and Clark (2006) a theme is '*something important about the data in relation to the research questions and represents some level of patterned response or meaning within the data set'* (pp. 87).

In line with Miles et al (2014) and elements of the process outlined by Braun and Clark (2006), the following process was followed when analysing and coding the data. It is important to note that only part of Braun and Clarks (2006) process was followed as codes were already developed according to the themes identified within chapter 5.

- A list of codes was generated based on the themes contained within chapter 5. A definition for each theme was provided. These codes and associated definitions are provided in table 8.2 below.

- Interview transcripts, documents, documentaries and field notes were all read through a minimum of once ensuring thorough examination and familiarisation with the data.
- The codes were attached to relevant chunks of text. For the documentary, notes were made and these were coded. In line with Bryman & Bell (2011), larger chunks of text were taken in some cases to ensure the context of the text was not lost.
- Each theme was then tabulated alongside the coded data attributed to them. This allowed the condensed data to be suitably displayed.
- All tables were then compiled into separate files according to themes and added to the case study database.

Theme	**Code**	**Definition of theme**
Resource integration	Resint	Resource integration refers to the process through which resources are made available through resource mobilisation for the focal beneficiary and how they integrate said resources.
Contextual variety	Convar	Contextual variety refers to the number of different states a resource can be used it. Contextual variety is an emergent property of use.

Design rules	DesRul	Design rules are seen as the common understanding of roles and purpose between actors that allow them to operate efficiently and effectively within their modules/service ecosystem. Design rules are synonymous with institutions.
Modules	Mods	Modules are resources, tasks or activities that are tightly coupled within but loosely coupled to the rest of the system.
Actor agency	ActAge	Actor agency refers to an actor's ability to act in a given context. It can refer to both enabling and constraining factors.
Value proposition design	VPDes	Value proposition design refers to the design techniques, methods and approach for the physical asset and service activities.
Technological advances	TechAdv	Technological advances refers to advances in technology that change the existing state of the system.
Value	Val	Value is attributed to individuals understanding of value. This can be derived

		in use or created and delivered in exchange.

Table 8.2. Coding items and definitions.

8.3 Findings

This section details the findings of the first study following analysis of the data as described in the previous section.

In presenting the findings, the output from the data reduction and data display phases for the DSMs, ASMs and DMMs are presented, followed by the growth gradient analysis that were derived from information contained within the matrices. A summary of these results are visually presented in the following figures. It important to note that whilst a DMM is presented, it contains the ASM (top left of the DMM) and the DSM (far right of the DMM), so all three matrices are presented in a single figure. The two DMMs presented are for the Warrior 510 platform. Figure 5.1 is before the two conflicts started and figure 5.2 is after the combat missions in both conflict zones ended. The activities associated with each number (for the columns and rows of the matrices) within the ASM are found in appendix 6. Whilst the components of the DSM have been labelled using a sequential lettering system. The component names themselves have been hidden for the purpose of intellectual property and systems knowledge that is owned by the organisation. For the growth gradient analysis, Bulldog 4, CVR(T) Samson and Warrior 510 are presented. Each growth gradient analysis has a number of important events tied to them, including key events from the Afghanistan and Iraq wars including the changes were requested, implemented and other key events, such as intensified fighting or a surge in different types of threats. It is important to note that whilst Bulldog 4 has been labelled with the Iraq events, these events are also applicable to CVR(T) and Warrior as all three platforms were used within the Iraq campaign and whilst CVR(T) Samson has been labelled with the Afghanistan events, these are applicable for Warrior as both platforms were used within the Afghanistan campaign. This approach reduces repetitive labelling and cluttering of the growth gradient analysis.

The findings for this study are now presented in detail.

8.3.1 Findings for study one

The following figures present the DMMs and growth gradient analysis.

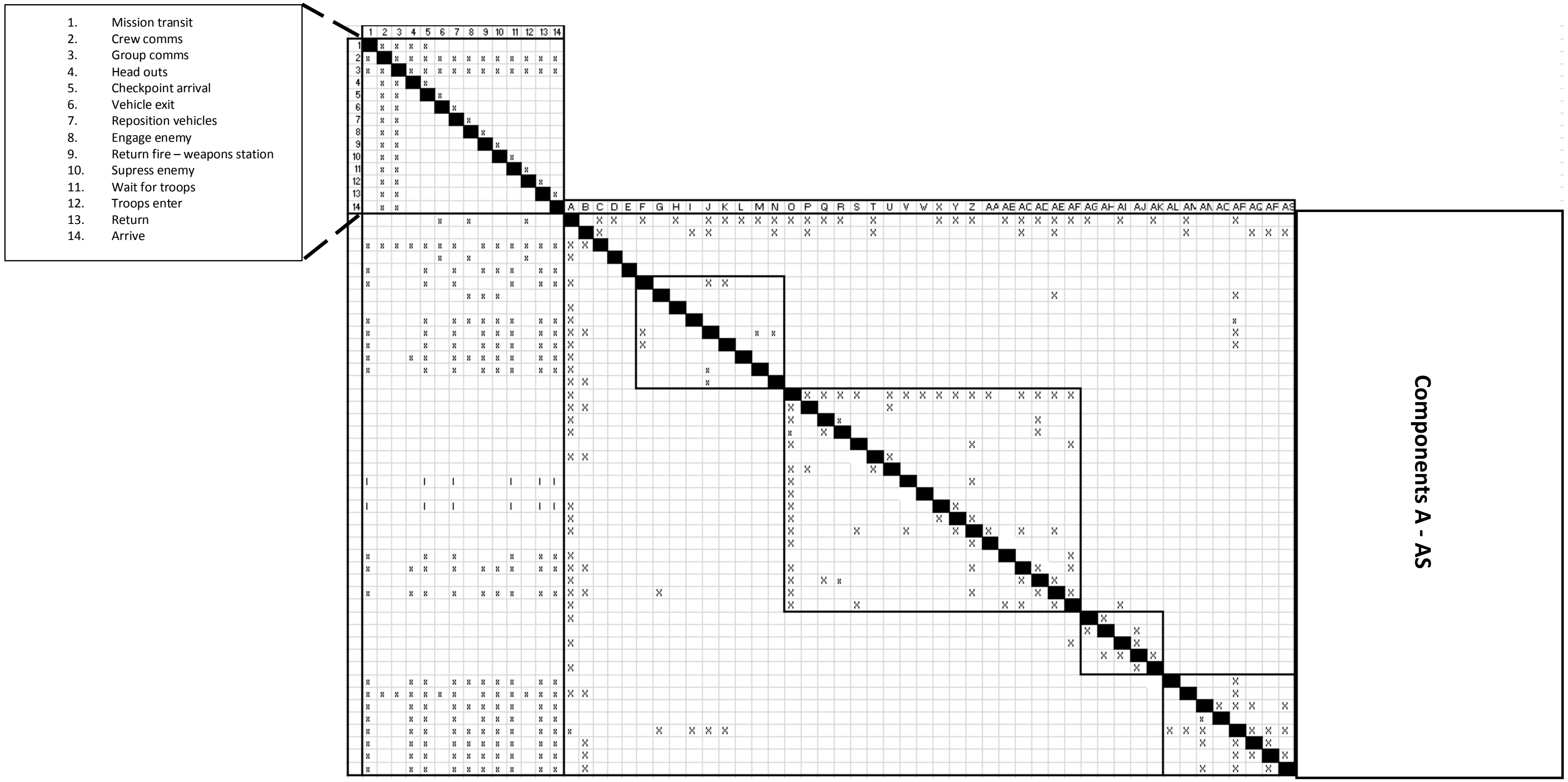

Figure 8.1. DMM of Warrior 510 before it entered Afghanistan or Iraq.

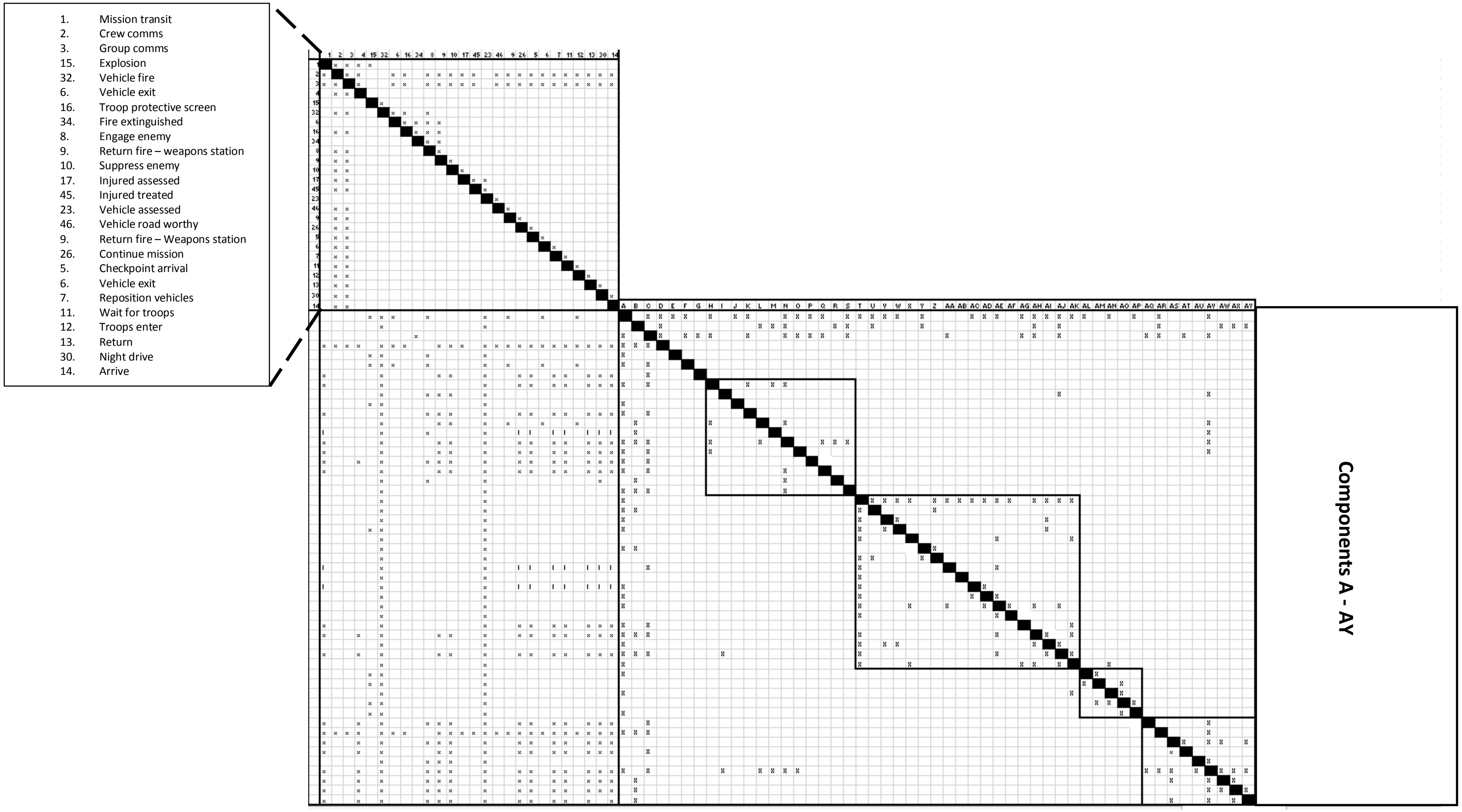

Figure 8.2. DMM of Warrior 510 after the Afghanistan and Iraq campaigns ended.

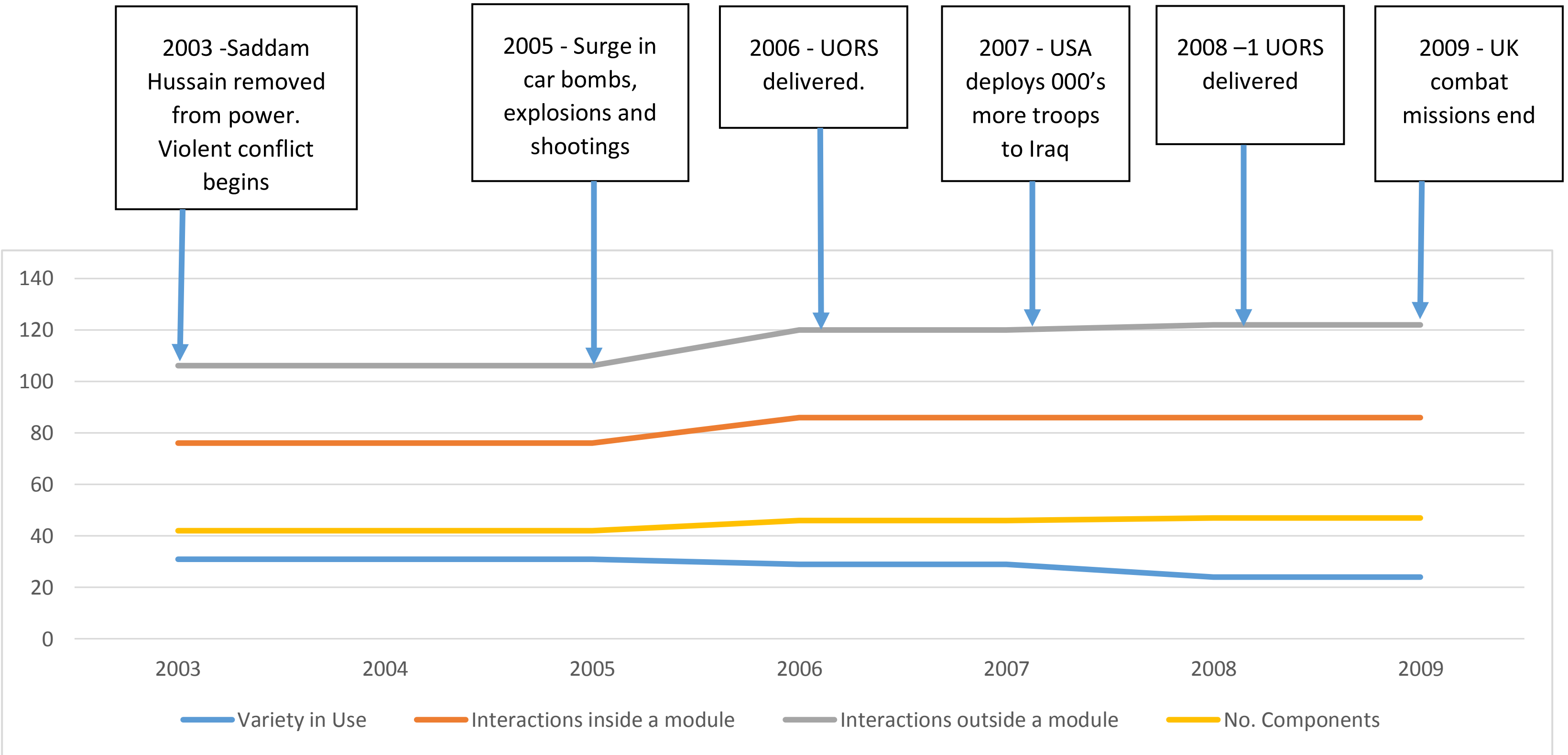

Figure 8.3. Bulldog 4 Growth Gradient Analysis.

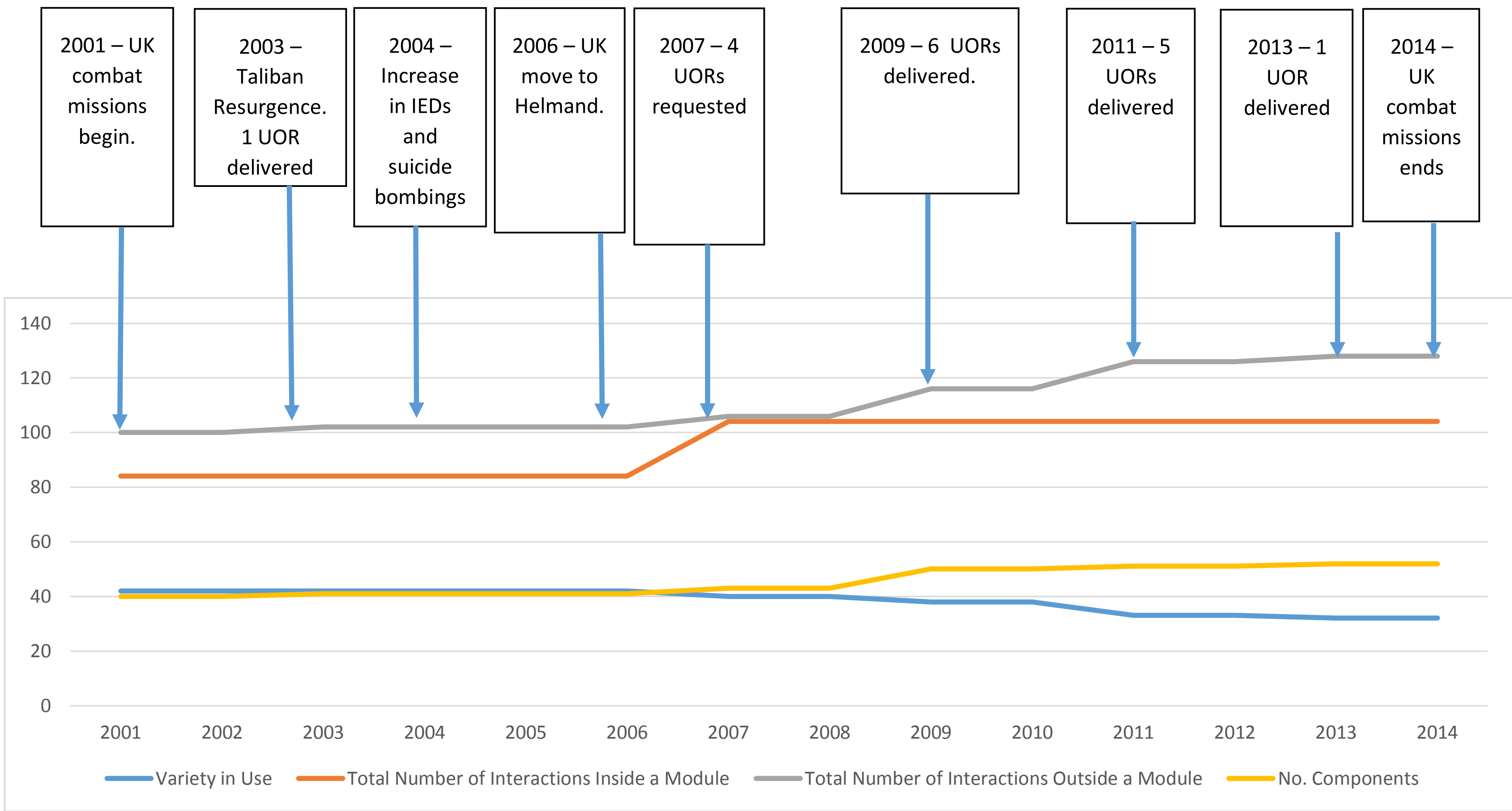

Figure 8.4. CVR(T) Samson Growth Gradient Analysis.

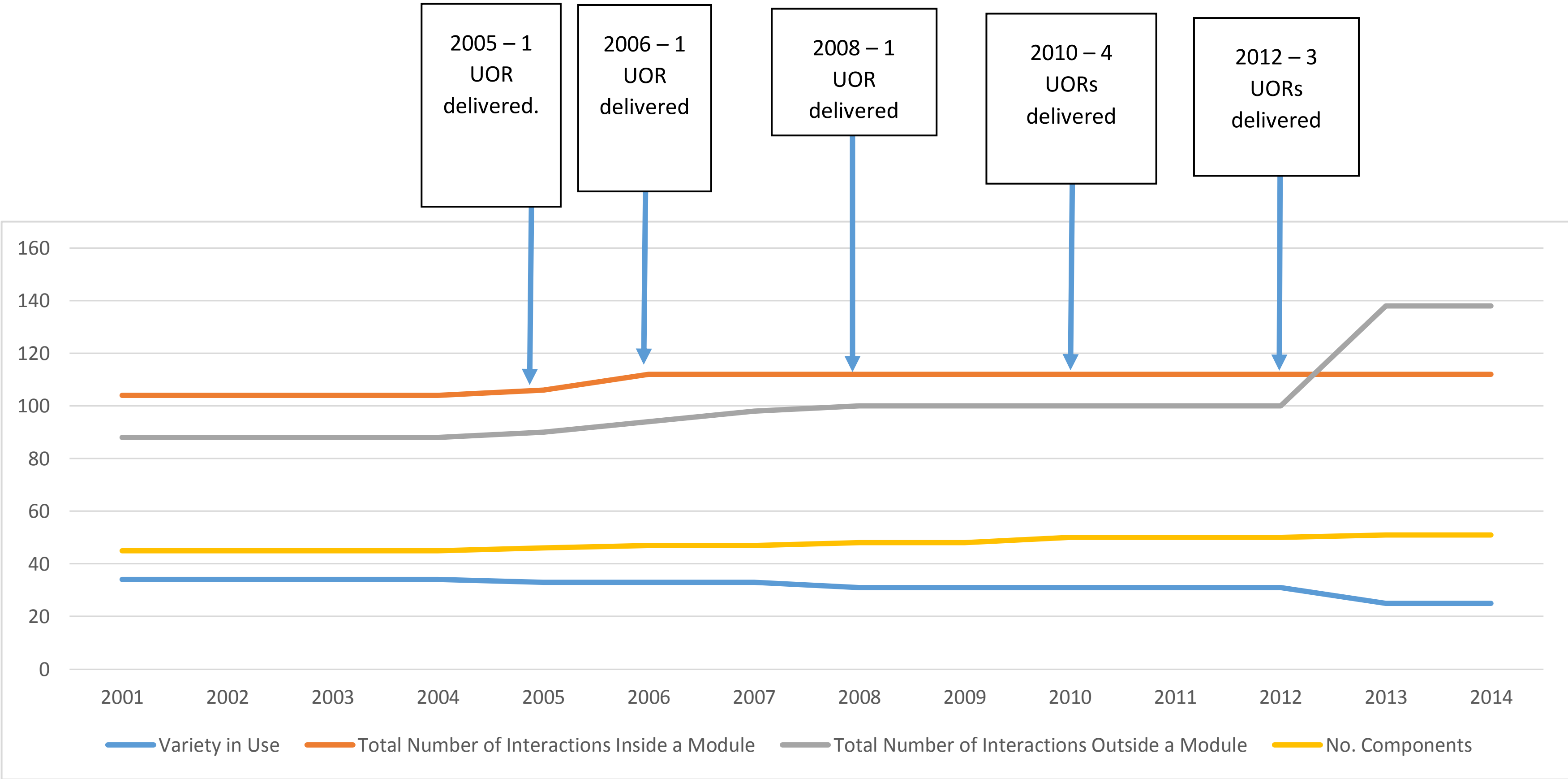

Figure 8.5. Warrior 510 Growth Gradient Analysis.

Within the matrices, it is possible to see the impact of design changes (UORs) on both the interactions occurring inside and outside of the vehicles subsystems (as presented within the DSM) and the number of activities conducted by the actors within the system (as presented within the ASMs). It can be seen that the number of interactions increases within the product architecture DSM whilst the number of activities and interactions between activities decreases or remains stable within the ASM each time a design change is implemented. Within the growth gradient analysis, it is evident that as design changes are implemented, variety is absorbed in most, but not all, cases (i.e., the number of activities reduces) and both interactions inside and outside of subsystems within the product architecture DSM increases. Whilst this would be expected as the number of components within the asset increases as a result of a design change, the findings show that interactions outside of modules increase at a greater rate than those inside of modules. This finding suggests that manufacturers find difficulty in managing design change complexity and integrating design changes that were not part of the original specification. This is supported in the following interview extract when discussing a design change and the reasons why the organisation struggles to manage the efficient integration of design changes in response to high variety use requirements:

"I think probably the major contributors, at the minute, is, as I say, we're working with a legacy fleet and the legacy fleets are where they are at. The chance to change some of those interfaces, within the life cycle of vehicles that's left, isn't going to happen".

In addition to this finding, it was found within the documentation analysis that these vehicles were designed prior to the organisation servitizing, suggesting the use of legacy vehicles, that were design for low variety, limits an organisations ability to efficiently manage the complexity of the assets architecture when designing for high variety, post production of the original asset.

This finding is consistent throughout the DSM and growth gradient analysis. Furthermore, the findings contained from the interviews highlight how there is a relationship between interactions both inside and outside of module boundaries increasing, as a result of design changes, and the through life costs associated with managing and maintaining the asset post design change. This is evident from the following interview extract and field note:

"Yes, I think legacy-wise it's just it tends to be cost prohibitive to retro-fit that to the fleet. So it's a big architectural change for all these vehicles".

Field note:

"Yes we managed to implement the design changes the customer wanted, but the timescales they provided and the legacy fleets we work with meant they were not designed as we would like from a through life cost perspective. I expect the through life costs will be high. Evidence so far suggests they will be, but we do not have enough data as the campaigns were so recent".

These findings also highlighted another property of use that was evident throughout the interview data that impacts the efficient integration of design changes within the existing architecture. This was the influence of urgent timescales dictated by the customer. This is further evidenced in the following interview extract when specifically addressing urgent timescales of UORs:

"…the fact of the matter is that the timescales of some of the UORs they're very ad hoc and they're very bitty as well. So one week you can be doing a modification to a turret and do it in a way that meets that timescale; six months later someone says, well actually, I'd like this modification, we didn't know that, we'd have done that bolt on instead of welding it on, you know, that sort of thing".

Whilst guided by the themes, this finding presents an additional theme that presents a difference between designing for high variety and designing for low variety; urgency

These findings have patterns of similarity across each of the platforms within both the growth gradient analysis and the textual data.

If we apply the logic of modularity theory described as modularity for low variety within chapter 2, we find some interesting insights that suggest designing for high variety is different to designing for low variety. The findings presented here would contradict what existing literature says in that modularity is an efficient strategy for managing complex products. With specific reference to autonomous module evolution and upgrades, the findings show that the organisation is not able to efficiently manage the architecture of the system to accommodate variety of use when design changes not part of the original specification are required after the vehicle has been designed and manufactured. This was shown by the growth gradient analysis, interviews and document data. This finds different results to Ethiraj & Levinthal (2004), who state that modularity is a useful strategy for managing complexity, and Pil & Cohen (2006) who propose that modules can evolve autonomously over time without having a wider effect on the architectures overall complexity. Instead, empirically support the argument put forward in the literature review that modularity can contain complexity if the design change is not a new functionality for the system. These findings therefore suggest two things. First, modularity for low variety is not suitable for contexts characterised by continuous change and high variety because existing approaches to modularity that successfully freeze the structure, interfaces and functionality of a product prior to production cannot cope with the emergent properties of use.

Second, designing for high variety has different requirements to designing for low variety because the boundary between design and context is now blurred. In extending the boundary of the organisations responsibility to use (i.e., the customers context), where they could be responsible for availability or outcomes (Smith et al, 2014), new inputs into design activities are created that are not always under direct control of the organisation. These are the urgency of the required change and the emergent and unpredictable nature of the customers' use space that forces the change i.e., contextual variety. This finding has not been accounted for in existing modularity studies as the organisation separated their production activities and the customers' use, with the latter deemed to be outside the boundary of the organisations responsibility. In finding these results, empirical support has been provided for Henfridsson et al (2014) who posit that modularity theory currently restricts post production design changes due to the organisation 'freezing' the architecture of a product and its associated functions early in the design cycle. Second, it supports Garud et al (2008) in finding a scientific approach to design that focusses on completeness, such as modularity for low variety, creates a number of problems for the organisation in environments characterised by continuous change. Finally, it adds empirical support for Ng & Briscoe (2012) who claim that existing design and manufacturing theories, methods and tools may not be suitable for servitized contexts and could potentially be contributing to the service paradox.

The above findings leads to the following propositions:

Proposition 1a. Post-production design changes that seek to absorb contextual variety increase design complexity and through life costs for the organisation when a design for low variety strategy is used.

Proposition 1b. The negative effect of design changes for the organisation are more significant in environments where contextual variety of use and the urgency for new resources is high as opposed to low.

Proposition 1c. Designing for high variety has different requirements to designing for low variety because the organisation has to account for the urgency of new resources and contextual variety in use, which cannot always be predicted in advance.

In addition to the DSM data, the ASMs and growth gradient analysis provides further interesting findings relevant to the research question. The ASM and the growth gradient analysis show that, in most of the cases, as design changes are implemented to accommodate the variety of use, the number of activities, for which existing resources could not cope with, reduces. Thus, the findings suggest as design changes were implemented, the customer was able to absorb the variety of use, as depicted by the reduction in use activities that emerged prior to the design change. The original design specification of the assets highlighted that in the perceived scenario of use (i.e., what the design specification thought the vehicle would be used for), the vehicles would be exposed to fourteen activities should the context remain stable through life. These activities were identified during the data collection stages and confirmed by the FSR's, design engineers and platform champions. When used in Iraq and Afghanistan, these activities increased as a result of the variety of use that came with a change in context and exposed the assets to activities they were not originally designed for. These increases reached a peak at the start of each campaign, before any design changes were implemented and represent the start point on the growth gradient analysis. It is important to note that the activities vehicles were exposed to were not necessarily uniform due to their role profile (i.e., is the vehicle an infantry fighting vehicle, a recovery vehicle, etc) and so the number of activities following the emergence of variety in use is not the same for all vehicles.

However, in some cases, the findings from the ASM and growth gradient analysis suggest that not all design changes were able to absorb variety as the number of activities remained stable post design change. Insight into the reasons behind this and how, whilst some design changes could not absorb variety in terms of reducing the number of activities that have emerged as a result of variety in use, they still improved the viability of the customers' value creating activities. An example of this is the air conditioning unit. This design change did not absorb variety as depicted within the growth gradient analysis and ASMs (i.e., it did not reduce the number of activities), but it did improve crew comfort during transit inside of the assets. By improving comfort, it kept the crew in a better physical state, improving their performance once they dismount and begin their mission by foot. It also provided the opportunity for the crew to conduct missions for a longer duration as they were not fatigued, dehydrated or exhausted by the desert heats that the assets were not originally designed for. This is highlighted from the field notes when discussing the DSMs with a platform champion:

"Changes like AC did not directly help the customer combat the enemy, but it did help maintain crew comfort inside the vehicles. Indirectly, when the crew dismounted they were in a better condition to perform their mission than they would have been had we not integrated AC into the platforms".

This finding suggests that variety is not always an emergent component of use that creates additional activities for the customer, but it can have an impact on actor performance within the existing activities. Namely, variety can inhibit an actor's ability to act either completely or optimally under certain conditions, presenting an additional variable for organisations to accommodate for in their design activities, actor agency. This is further supported from another interview extract, where an engineer discussed the impact of environmental conditions to human requirements and asset performance:

"Storage is a big issue. It sounds trivial but in theatre they had a real problem with water, because they had to drink, what was it?...Something like that, so if you go out for any length of time, three or four day mission, suddenly you've got to store 60 litres of water on a vehicle for a crew of three or something like that, well where's that going to go? Well, we didn't plan that in the design because it wasn't a requirement".

This finding shows an intimate entanglement between asset rigidity, actor agency and contextual variety.

These findings lead to the following proposition:

Proposition 2a. Asset rigidity can inhibit an actor's ability to act in high variety contexts.

Proposition 2b. Designing for high variety has different requirements to designing for low variety as it requires the organisation to accommodate for the entanglement of human agency, contextual variety and asset functionality in use.

This proposition provides empirical support for Ng (2013) and Smith et al (2014) who conceptualised that modularity from the perspective of use and context requires the organisation to account for the actors, their resources and their agency within the design of their value proposition.

Thus far, the findings have shown that as an organisation servitizes and they integrate design changes to accommodate variety in use and maintain viability of the customers' value creating system, the customer is able to absorb variety but the design complexity of the asset increases, presenting potential implications for through life costs and management of the assets architecture. In finding this relationship, it presented a number of factors that make designing for high variety different to designing for low variety. Primarily, these factors highlight that when designing for high variety an organisation has to account for a number of new variables that they may not necessarily be able to control given their emergent and dynamic properties. This is supported by the following interview extract when discussing the philosophy behind UORs:

"The philosophy behind it, right, that's a good question. I guess fundamentally needs will arise and needs will arise in an emergency operational environment at any time, we can't control that, or at least we find it very difficult to control those emergent properties of the environment which result in emergent needs".

These findings provide empirical support for the propositions put forward by Ng & Nurudupati (2010) who posit that organisations servitizing need to account for the customers' use context and find new, multi-dimensional ways of thinking about design and production. With specific reference to new ways of thinking about design and production, one participant suggested technology is allowing these new ways of thinking to emerge. In particular, when discussing 3D printing, it was found that technology could open up new opportunities to create hybrid architectures for primarily material assets to allow for greater levels of standardisation and variety:

"Now as we move further forward into the future where we've expecting quite a lot of disruptive change, which has been driven by technology, we'll have to put much more flexibility, much more adaptability as well, into the designs of our future products in order to meet these changing requirements. Now the reality is, that I think if the two approaches are mentioned, you wouldn't want to kind of throw one out of the window as the likelihood is there's going to be some hybrid model of the two where you can produce products which are adaptable, which are flexible, and at the same time, can produce new products or even modify existing ones for a more UOR type approach. For that you need engineering capabilities of a new order I would suggest".

In another interview extract, new ways of thinking about production and variety was discussed, with a greater insight into limitations of the current process the customer follows when ordering assets from the organisation. This is presented in the following extract:

"Bulldog went into service in 1986, it'll be in service in 2040. But there's not much opportunity for bringing… within that life cycle, you know, saying, "Ah yes I've got a better

way of making this widget, well that's nice, I'll look at it in 30 years when I want some." That's a bit of a killer. Now I think… personally I think there's an opportunity for a paradigm shift. If you then get the customer having stuff on continual production, rather than trying to build a thousand vehicles, 200 vehicles in 12 months, 18 months, two years, one big build and then they have a rolling manufacturing plant for 20 or 30 years. I think if actually there could be a modular manufacturing approach going in, we will run the factory with new vehicles".

This highlights the role of technology in acting as an enabler for new value propositions that focus on use and outcomes where assets can be tailored on a continuous basis. Primarily, emphasis was placed on the digital nature of 3D printing and the unbounded materiality offered by the technology that could see individual platforms modified based upon use requirements. This was brought to the fore in the following extract from a CDE initiative highlights the potential opportunity digital technology holds in serving use:

"The current response time to develop and deliver a novel concept to theatre is not optimal. This challenge seeks to demonstrate how additive manufacturing may be used to increase re-configurability in military systems. We want to understand whether additive manufacturing could be used to rapidly build, adapt or modify equipment to provide enhanced functionality".

Of interest is the reference CDE make to the sub optimal capabilities of traditional manufacturing, suggesting the approach they discuss with respect to designing for high variety, is only made possible through advances in alternate, digitally enabled manufacturing technologies such as 3D printing.

Finally, with reference to 3D printing, design complexity and interface specification, an interviewee said the following:

> *"… if you suddenly said, "Well, I'd like to put a mine plough on the front of this vehicle, I've got one here, what do I need? Oh well, if I do these… take these interfaces, let's print all of this and let's then mount that on there." So that's the type of flexibility I'm more thinking around. So you're taking things rather than …Yes, so in a very short space of time you've gone from it not having that capability to suddenly, yes, I can now mount this and put it on".*

The implication of this finding is that the design freedom and digital materiality associated with 3D printing can make the integration of new components easier for two reasons. First, the binding between form and function does not have to occur prior to production of the original asset and instead, can be bound following the emergence of variety in use. This has a secondary implication that demand can be satisfied at the point of use, where form and function are almost permanently delayed until the resource is required. Second, as a result of the digital nature, geometric freedom and economies of one, 3D printing could moderate design complexity. Furthermore, 3D printing allows for novel designs to be produced such that they can efficiently and effectively modify existing interfaces to accommodate new functionality without adding complexity into the system (i.e., it would allow for the efficient modularisation of new modules within the architecture or the efficient integration of components into existing modules). Furthermore, they can be produced on an individual platform and component basis. Thus, rather than being able to draw on a single design hierarchy, 3D printing allows customers' to draw from a range of design hierarchies and thus material assets become more flexible in use because components are now product agnostic. Therefore, whilst 3D printing results in a material component, it is able to share characteristics of digital technologies as described by Yoo et al (2010; 2012), Ng (2013) and Henfridsson et al (2014) because of the additive nature of the process that is driven by software and digital files, as opposed to fixed tooling and moulds that subtractive techniques used to create a material component. However, it is important to note that this finding does not cover specific design principles that may be required to allow this to happen, such as engineering trials and testing of components and whilst they do show the technology presents an opportunity for new hybrid architectures, where physical and digital components are mixed to serve use and context, it does not show how the organisation would manage or create these hybrid architectures so that they can be implemented and operated efficiently and effectively.

This leads to the following propositions:

Proposition 3a: Existing manufacturing techniques restrict an organisations ability to design for high variety.

Proposition 3b: Technology is an enabler for designing for high variety because of the affordances of digital materiality.

In discussing 3D printing, an interview extract was presented that discussed purchasing habits of the customer (i.e., bulk ordering their assets from the organisation). This has interesting implications for the customers' institutions because when bulk ordering the assets, where each vehicle is identical to the next, the customer creates their practices and behaviours (I.e., institutions) around the asset that is characterised by a functional rigidity in use. Insight from further interviews highlighted how the rigidity of the asset during peacetime, when variety of use is low, has implications further down the line when variety during a conflict is high:

"…when IEDs came to the fore then there was lots of activity including upgrades mods to vehicles as well as purchasing a few vehicles and changing of practices in training and all the rest of it…Now, their training might have prepared them for a certain environment and the use of that vehicle might be to do a certain profile so you go for this sort of distance, your vehicle might idle for so long, deal with these threats but then when all that changes, that is a very different profile so it's concept of use, you could end up using a vehicle for something that it wasn't designed for because you're out there in the field and this is what you've got available to yourself".

Combining this insight with earlier extracts, shows the limitations of producing all vehicles against the same specification at one point in time. These findings suggest that in focussing on functionally static physical assets, customers' training, practices, behaviours and institutions more generally are formed around these assets. Given the rigidity of the asset and that institutions are formed around these, organisations need to integrate resources around existing institutions (i.e., practices) when urgency for those resources is high. This finding presents a link between urgency and institutions. Namely, when urgency is high, organisations need to design the new resources around these institutions as there is no time to re-align existing institutional arrangements (i.e., create new customer practices, knowledge and skills) even when a more optimal design solution may exist. If the resources do not align with the existing institutions, it would inhibit an actor's ability to apply their agency and resources for the co-creation of value.

This finding therefore highlights how the rigidity of the asset creates tensions between institutional arrangements, designing for high variety and value creation. Furthermore, it finds that institutions are the higher order design rules of the system and modules are tasks and activities made up of operand and operant resources. Modules as tasks and activities aligns with existing thinking in the service modularity literature (Starr, 2010).

This leads to the following propositions:

Proposition 4a. Designing for high variety has different requirements to designing for low variety because the organisation has to account for the customers' institutions in their design activities.

Proposition 4b. At a higher level of conceptualisation, modularity-in-context views institutions as design rules, modules as resources and the service ecosystem as the architecture.

Finally, the collective outcome of the findings leads to a final proposition:

Proposition 5. Designing for high variety has different requirements to designing for low variety because the entanglement of design and context introduces new variables to the organisations design activities that cannot always be controlled or predicted in advance.

8.4 Discussion

The research objective and research question were presented at the beginning of this chapter. The discussion now presented is guided by these.

To address the research question, this thesis drew upon the general understanding within the modularity literature that design and production activities were flexible before the offering was released to market (MacCormack et al, 2001; Buganza & Verganti, 2005) allowing organisations to scale and replicate their offerings but limiting their ability to integrate functional design changes post-production (Yoo, 2013; Henfridsson et al, 2014). Furthermore, what happened beyond the point of exchange and within the customers' use context was not deemed relevant to the organisation as value was created in exchange as opposed to use (Kimbell, 2011). Within the OM and servitization literature, where emphasis is placed on use and context, scholars claimed existing manufacturing theories, tools and methods as described within this thesis were not appropriate (Ng & Nurudupati, 2010; Smith et al, 2014). In particular, Ng (2013) specifically references modularity theory in its existing form (modularity for low variety) as being too product, function and statically orientated for a servitized context characterised by continuous change and high variety. Furthermore, Ng & Briscoe (2012) posited that the physical asset may contribute to the service paradox because of the rigidity of its functionality imposed upon the customer through the use of a modularity for low variety approach resulting in either the customer or organisation to rely upon human resources to absorb variety. The suggestion from these authors was that organisations need to accept a redesign of the physical asset to absorb variety would allow them to scale and replicate across contracts because variety is absorbed by the asset, as opposed to human resources. However, they did not empirically show this from the perspective of design. This thesis built upon the existing design literature, modularity literature and the emergent arguments within the servitization literature to empirically explore their claims. In doing so, this thesis identifies a number of propositions that generate a greater understanding as to why designing for high variety has different requirements to designing for low variety and these were identified by addressing the limitations of a modularity for low variety approach in a context characterised by high variety and continuous change.

Identifying propositions that find a number of different reasons why designing for high variety has different requirements to designing for low variety when applying existing manufacturing theories within a servitized context therefore contributes to the design, modularity and servitization literature. First, it contributes to the servitization literature by providing an empirical exploration as to whether the physical asset, designed using a modularity for low variety frame, contributes to the service paradox as a result of its functional rigidity and the negative impact on through life costs resulting from increased design complexity. Second, it contributes to the design and modularity literature in a number of ways. First, it provides empirical support for Henfridsson et al (2014) who posit modularity limits an organisations ability to integrate design changes post production of the original asset as a result of the material characteristics of the offering. Second, it contradicts existing literature that states modularity is an efficient strategy for managing complexity (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Pil & Cohen, 2006). Instead, the findings show that in contexts where new functionality is required post production, organisations struggle to contain the design complexity because it is not possible to align the new functionality with the existing design rules and this is even more difficult when urgency of resource requirements is high. Third, it contributes by viewing the phenomenon through a S-D logic lens. Drawing on S-D logics understanding of value and resource integration, this allowed the researcher to highlight a number of reasons why designing for high variety has different requirements to designing for low variety. Modularity has primarily been studied from a G-D logic perspective where value was embedded within the asset and transferred to the customer at the point of exchange. This understanding drove OM strategies of mass customisation and product variety that created variety for customers within the organisations design and production activities. This implies the form the organisation exchanges with the customer fulfils their needs at the point of use, because the organisation has frozen the outer environment that their offering interfaces with into a stable set of user requirements and performance attributes (Garud et al, 2008). Viewing value in this manner led firms to believe that integrating different modules prior to use was a satisfactory way in which to accommodate different customer requirements. However, as discussed in chapters 2 and 3, understanding value as embedded utility (i.e., value is embedded in the offering when produced) provides limited insight into how value is actually created and the role contextual variety, institutions, agency and emergence plays within this process. Fourth, it supports Ng & Briscoe (2012) in that the asset can absorb variety, as shown in the growth gradient analysis. However, new ways of designing the asset are needed. The interviews suggesting a hybrid architecture incorporating both material and digital resources would be a suitable design approach for the organisation to take if they are to design for high variety.

In finding that the existing modularity for low variety frame was not suitable for contexts characterised by continuous change and high variety, a number of propositions were presented. These were: (1) Designing for high variety has different requirements to designing for low variety because the organisation is constrained by the urgency for new resources and the inability to predict resource requirements as a result of emergent use contexts. (2) Designing for high variety has different requirements to designing for low variety as it requires the organisation to accommodate human agency in use. (3) Technology is an enabler for designing for high variety due to the unique characteristics of digital materiality that does not require form and function to be bound during the design phase. (4) Designing for high variety has different requirements to designing for low variety because the organisation has to account for the customers' institutional arrangements. Taken together, these four propositions lead to the final proposition that states: (5) Designing for high variety has different requirements to designing for low variety because the entanglement of design and context introduces new variables to the organisations design activities that cannot always be controlled or predicted in advance.

The first proposition suggests that additional variables become inputs into the organisations design and production activities as a result of extending the boundary from exchange to use, where the customer is an endogenous variable of the system. Namely, these variables are emergence (i.e., contextual variety that emerges during use) and urgency (i.e., the speed at which new resources are required by the customer in use). This proposition relates to modularity, product variety and value creation. In existing modularity literature, creating variety at the point of exchange is deemed to satisfy customer requirements (Pine, 1993; Starr, 2010). In actual fact, in serving contexts, variety is created during use as an emergent property of the context within which the customer is using the asset (Smith et al, 2014; Green et al, 2017). Resource requirements that subsequently effect a customers' ability to co-create value are thus determined at the point of use and may not be possible to predict in advance due to the dynamic and emergent properties of use and value creation (Maglio, 2015). Furthermore, the impact of contextual variety that emerges over time on a customers' ability to co-create value will have an impact on the urgency placed on the organisation by the customer that subsequently impacts the speed at which the organisation needs to develop or find new offerings to accommodate variety at the point of use. The findings also present a relationship between the propositions, namely proposition 1c and 4a. Proposition 4a acknowledges that organisations need to account for customers institutions within their design activities. This was especially prevalent when urgency for new resources was high as opposed to low. This highlights that the system can be modularised (i.e., thin crossing points created) in different ways depending on the level of urgency for new resources. In conditions of high urgency, the findings showed how the organisation had to design around existing institutions (i.e., customer practices, behaviours and training) whereas in conditions where urgency is low, the organisation can work with the customer to rearrange institutions to design a more optimal solution that allows them to achieve their outcomes. This discussion point has a number of implications for organisations designing for high variety as it shows reinforcement effects between different variables.

Proposition 2 suggests a shift in emphasis from designing for low variety, where function of the offering is a primary, to designing for high variety, where human activities and augmenting their performance in use should be the primary focus of design. Importantly, proposition two recognises that this can be achieved through the constant readjustment of resources in use to support the customer in the achievement of their outcomes. Proposition two therefore brings to the fore that function is a surrogate of use and organisations need to design and manufacture assets around human activities (Smith et al, 2014). Finding that variety had an effect on an actor's ability to apply their agency showed the importance of understanding this when designing for high variety. Furthermore, it provided empirical support for Ng (2013) who posited that agency in use was an important characteristic of use that organisations needed to account for if they were to design for high variety use contexts. The implication is that thick crossing points would emerge at the point of use if the organisation did not account for the actor's agency. Finally, whilst these findings support Smith et al (2014) by showing design needs to incorporate human activities, it does not provide evidence to support that if they do not, it could contribute to the service paradox.

Proposition 3b shows how technology is an enabler for designing for high variety. Whilst this finding was identified in the literature, it was supported throughout this study and reasons why emerged from the dataset. The main finding showed the flexibility of 3D printing. Namely, the binding of form and function can be delayed until a specific resource is required allowing greater flexibility in the configuration of resources in use and the ability to integrate resources from different, as opposed to single, design hierarchies. Furthermore, an important finding was that it could complement existing manufacturing technologies because of its geometric freedoms that would allow new interfaces for components to be created without increasing the complexity of the assets architecture. However, it was noted this would require new design approaches of a new-order, with suggestions that a hybrid-architecture of digital and physical components making up the whole. This would support Green et al (2017) who propose that a challenge for S-D logic orientated organisations and scholars is finding the right boundary between variety (digitally enabled) and scalability. Whilst the findings found this, and presented a number of reasons why, it is outside the scope of the thesis to present specific design characteristics. Finally, this finding would provide empirical support for Ng & Briscoe (2012). The findings showed that a redesign of the physical asset could allow the asset in use to absorb variety, as opposed to human resources. This means this thesis contributes to the design literature by showing acceptance of the physical assets use as within the boundary of the organisations design activities results in a new frontier for design and OM.

Finally, proposition 4 brings to the fore the role institutions play in resource integration, modularity and design. Notably, it was found that in situations of high urgency, organisations need to account for the existing institutions in their design activities. This was found to be the case because the customer, when urgency of resource requirements are high, does not have the time to modify their existing institutions. This impacts the organisations design activities as it means they have to design around their existing institutions and whilst not always a difficult task, an optimal solution may not be sought. An important part of this finding relates not only to the organisation, but also the customer. The findings show that in order to modify, adapt and tailor their equipment on a constant basis, two things are required. First, the customer needs to be more flexible and adaptable for new resources. Second, the organisation needs to design resources that can be integrated without the customer needing to apply many, if any, of their resources for the new resource to perform its function and absorb variety in use. Thus, these findings build upon the arguments put forward by Edvardsson et al (2014) and Lusch & Vargo (2014) who posit that resource integration is governed by actor generated institutions and that these shape actors practices and behaviours within a system during the act of value co-creation. Furthermore, it brings to light that designers creating thin crossing points need to account for more than technology and functionality in design and account for human activities within their design process. This finding therefore provides empirical support for Smith et al (2014) who argued organisations serving high variety use contexts need to account for human activities during the design of the value proposition.

Taken together, the findings therefore show the relationship between the design of the physical asset, use and value creation is more complicated than has been described in the literature to date. Furthermore, it highlights that a physical asset is not merely a stable platform of fixed functionality that new service activities are coupled to support efficient operation (Baines et al, 2009b; Spring & Araujo, 2017), but is a carrier of competence that is best placed to absorb contextual variety across different times and space given it resides within the customers' context of use (Vargo & Lusch, 2004; Ng & Briscoe, 2012). This description is a fundamental difference to the role of the physical asset within either an exchange or use based relationship and provides insight into the different requirements of design within the two approaches. More specifically, with advances in digital technologies it aligns closer to the concepts of design proposed by Manzini (2011) and Kimbell (2011). For them, design is not the end result, but instead the design integrated by the focal beneficiary is a platform for action and that fully specifying, imagining and planning for the design in advance is not possible given the purpose of the design can change dependent on the value creation requirements.

In summary, this study finds designing for high variety has a number of different requirements to designing for low variety. Whilst it is agreed that the physical asset is best placed to absorb contextual variety, existing manufacturing theories, tools and methods, with specific reference to modularity, limit an organisations ability to efficiently and effectively integrate functionality into the asset once it has been designed and produced against the original specification. A number of reasons for this were found within the study and they were directly related to the use of a modularity for low variety approach in contexts characterised by high variety and continuous change. The results of this study provided a number of reasons why designing for high variety has different requirements to designing for low variety and in doing so, has provided a suitable foundational from which adequate theory can be built around the concept of designing for high variety as a process of resource integration.

Reflecting on the research objectives, this study finds that designing for high variety has different requirements to designing for low variety for a number of reasons. Namely, extending the boundary from exchange to use introduces additional variables within the organisations processes that may not necessarily be within their control. Second, designing for human activities, as opposed to focussing on function, becomes central and introduces not only a human element into design, but a prerequisite that intuitional alignment between the organisation and the customer is an important consideration within the design and production processes of the organisation. Therefore, when designing for high variety, it is apparent that whilst function is important, it is a surrogate of use. Finally, in presenting a greater understanding of why designing for high variety has different requirements to designing for low variety, it was possible to generate a greater understanding to factors that would influence whether a system migrates toward a more modular state for resource integration or not, which has important implications for organisations seeking to modularise use for efficient and effective resource integration.

The review of the design, modularity and S-D logic literature in chapters 2 and 3 highlighted a number of gaps in our understanding of the design from the perspective of use and outcomes. To date, it can be argued that there has been little understanding as to why designing for high variety has different requirements to designing for low variety; this study has begun to address these gaps from a S-D logic perspective. Furthermore, in partially addressing this question through an investigation into the limitations of using a modularity for low variety frame within a context characterised by high variety and continuous change, this study has begun to converge on a foundational theory of modularity-in-context that had yet to be addressed within the literature. However, whilst it has supported a number of claims in the literature and presented a number of new themes and connections among them, a conceptual framework for designing for high variety and modularity in context has not yet emerged in this part of the study. Notably, this study sought to identify the limitations of designing for low variety within contexts characterised by high variety and continuous change.

Chapter 9: Study Two: The Effect of Use Complexity and Design Change Complexity on System Viability

9.1 Introduction

This chapter provides the quantitative component of the thesis. Drawing upon the literature in chapters 2 and 3 and the findings presented in chapter 8, the second study of this thesis explores the effect of use complexity and design change complexity on system viability. Specifically, it investigates whether design changes from the perspective of both use and design have a positive relationship with system viability.

In similar vein to study one, this study focusses on the organisations use of a modularity for low variety frame in a context characterised by high variety and continuous change to statistically check if a relationship between variables exists. Thus, this study remains exploratory as opposed to explanatory, but does seek to explore a set a hypothesised relationships between (1) *Use Complexity* and *System Viability*. (2) *Design Change Complexity* and *System Viability.* (3) *Design Change Complexity* and *System Viability* moderated by *Use Complexity*. The relationships between these variables and how they were identified will be detailed within this chapter.

Simply, the primary objective of this study is not to confirm (or reject) theory, but to understand the effect design change complexity and the customers' use context has on system viability. Thus, by examining how system viability is affected by the complexity of design change complexity and use complexity will provide greater insight into designing for high variety and help address the research questions and research objective.

This chapter is divided into six further sections. First, section 9.2 presents the conceptual development of the quantitative model. Second, section 9.3 presents the hypothesis to be tested within this study. Third, section 9.4 presents the data analysis procedure that includes the unit of analysis, construct definition and measurement items, data sources and sample size. Section 9.5 presents the research method and specification of the model. Fifth, section 9.6 presents the findings of this study. Finally, section 9.7 presents the discussion of this study and compares and contrasts the results against the existing literature before summarising the main contributions of this chapter.

9.2 Conceptual development

As detailed in chapter 6, the specific research question for this study is:

RQ1(b): Does design change complexity affect system viability greater under a higher use complexity?

To support the quantitative research, it is important to start from the literature review and the qualitative study conducted in the previous chapter. First, the following points made in the qualitative chapter are relevant to this study and provide an important start point as it allows for comparison between the findings within the first study and the literature in order to inform the development of this study. Furthermore, additional points have been derived from the growth gradient analysis to inform this study based upon some of the propositions put forward in the qualitative study.

First, customers request a design change when contextual variety affects their context of use and system viability (i.e., the ability to achieve outcomes and co-create value).

Second, use was described as a number of tasks and/or activities between the actor leaving the compound and returning to the compound. Variety in context would increase the number of tasks and/or activities required by the customer in use, suggesting variety made use more complicated. This thesis will now refer to this concept as use complexity.

Third, an organisation integrating a design change following a modularity for low variety frame would struggle to contain complexity of the architecture due to restrictions placed on the architecture when originally designed and frozen prior to production.

Fourth, design changes varied in respective levels of complexity, with some design changes more complex than others to integrate. The relative impact of higher or lower complexity on system viability was not discussed.

Fifth, the growth gradient analysis showed as design complexity increased, use complexity decreased, suggesting the more complicated the design was the more successful it was in use, however this was not conclusively shown.

Sixth, the organisations viability would decrease as a result of design complexity as it increased through life costs, however it was not clear how this affected the customers' system viability (i.e., the value co-creating activities, outcomes and wellbeing of the customer).

By deconstructing the qualitative study, it is possible to conceptually develop the quantitative study. This is done by drawing upon the literature.

Whilst a number of studies within OM have explored modularity and performance (viability) from the perspective of the organisation (e.g., Jacobs et al, 2007; Jacobs et al, 2011; Vickery et al, 2016), very few have from the perspective of the customers' context of use. This stems from the understanding of value inherent within the OM discipline that views value in exchange. Whilst firm orientation remains prevalent, studies within OM and servitization have recently adopted a dual approach of customer and provider with an understanding that value is co-created in context (e.g., Smith et al, 2014; Parry et al, 2016; Green et al, 2017). These studies have generally aligned with a S-D logic understanding of value and resource integration. In recognising value is created in use, greater consideration has been placed on resource integration and resource density. In focussing on the customers' context of use, the servitization literature proposed that use is more complex to serve as a result of contextual variety that is seen as a property that the organisation needs to manage if they are to successfully serve the customer in use (Batista et al, 2012; Green et al, 2017). This was also empirically shown in chapter 8. Given contextual variety is a property of use, it is suggested that this could have an effect on the customers' ability to co-create value. This is because resources available in context may no longer hold the same value as they once did (Peters et al, 2014) because variety threatens the original design purpose (Ng et al, 2011) and has made the system shift in state (Schilling, 2000) and become more complex for the customer to operate within (Ng, 2013). Furthermore, variety makes resource requirements difficult to predict in advance because they are an emergent property of the service ecosystem and thus it is increasingly difficult for organisations to proactively design and integrate resources to absorb variety (Batista et al, 2013; Maglio, 2015). Thus, whilst the literature has historically found that new resources lead to optimised resource density and an assumed improvement in the customer's value creating activities, the recent S-D logic and servitization literature has suggested that the perceived benefit of new resources that satisfy the needs of the customer are only useful if they can be integrated and used by the customer to absorb contextual variety and improve their performance in use. Thus, it is possible to observe that whilst design changes have a relationship with the system viability (i.e., value creation), the relationship is potentially moderated by the use of those resources in the customers context of use.

Within the OM and modularity literature, there is clear recognition that complexity plays a role in both product and process modularity. Complexity has been at the heart of modularity since Simon (1962) discussed it as a method of managing complex systems. Ulrich (1995) suggests a modular architecture is less complex than an integral architecture because of its one to one mapping of function and physical component whilst Baldwin & Clark (2000) specifically refer to modules as containing complexity from the rest of the system. In more recent studies, Pil & Cohen (2006) put forward that modular systems can evolve autonomously over time without effecting the overall complexity of the modular architecture and Ethiraj & Levinthal (2004) highlight that modular systems are useful for managing complexity. However, as noted in the qualitative study, this thesis has found results that find conditions that these assumptions may not hold. Most recently, Vickery et al (2016) studied the moderating role of complexity on product and process modularity's effect on new product introduction (NPI) performance. They define complexity using a NK-type metaphor where N refers to the number of components within the product and K the distinct number of process modules required to produce the product. They determined that complexity would be high if product and process modules contained a high number of components/processes. Thus, whilst complexity is an attribute of modular systems, their study measures complexity quite crudely by attributing it to the number of components within a given system. Within their study they performed a hierarchical regression to analyse the relationships between the variables within their model. Whilst the effect of product modularity on new product introduction performance was positive but diminishing when interacting with high complexity was a logical and expected finding, it is their results for process modularity and complexity that were most interesting. Process modularity had no main effect on NPI, but when interacting with complexity to affect new product introduction performance the result was positive. This appears counter intuitive, as it presents findings that show as complexity increases, marginal returns for process modularity increase. Whilst the authors attempt to explain this result through a discussion of 'over modularisation' as discussed by Garud & Kumarswamy (1995) and Ethiraj & Levinthal (2004), they struggle to fully explain why this result occurred. However, despite emphasis in current research on the role complexity plays in NPI performance, the effect of complexity in design (product modularity) on use and outcomes as determined by the focal beneficiary has not been explored. However, their understanding of complexity does not align with that defined within this thesis and opens up further opportunities to explore the concept of complexity in design on use and outcomes. This thesis argues that their definition aligns more with complicated as opposed to complex, as they are simply adding up the number of components and processes in a linear fashion. Instead, complexity within this thesis refers to interactions between interdependent components that occur or emerge in non-simple ways. For example, the first study showed how interactions emerge outside of modules as opposed to inside, making the management of the architecture more complex as the non-simple interactions are now spreading beyond their module boundaries to interact with other parts of the system. We therefore argue that Vickery et al (2016) do not align with our definition of complex and instead, their measure of complexity is treated as a measure of how complicated something is.

Whilst intuitively, the complexity of the design change would not have implications on the outcomes achieved by the customer in use, assuming they had they agency to use the design, the growth gradient analysis suggests there may be a relationship between the complexity of the design change, the customers' use of the asset and their outcomes in use. In line with the definition of system viability provided in chapter 2, where system viability is defined as a measure of wellbeing of a focal actor's value creating activities, this definition allows us to replace outcomes in use for system viability to remain consistent with the literature review. However, this has yet to be conclusively shown nor statistically examined. Whilst it has not been examined in the literature, the importance of examining this concept is to explore whether design change complexity would have implications for designing for high variety or whether it is simply an outcome of the limitations associated with a designing for low variety frame within a context characterised by high variety and continuous change. Indirectly, this would help address calls from Batista et al (2013) to understand how a firm needs to design for variety so that co-creation of value in use can be optimised without threatening organisation viability.

Given this case study focusses on the UOR process, using modularity for low variety within a context characterised by high variety and continuous change, reconfiguring their material assets based on the customers' context of use, the start point of this study is the design changes and the end point the viability of the customers' context of use. From the qualitative study, we know the viability of the organisations system is reduced because of through life costs increasing as a result of increased design complexity during the design changes. However, the qualitative study, beyond establishing that the resources integrated post emergence of variety in use absorbed said variety, did not identify whether the changes actually improved the customers system viability. Combining this with the discussion within this section, it is possible to identify three main variables; design change complexity, use complexity and system viability. The definition and measurement of these constructs is developed in section 9.4.2.

Based on the observations and conceptualisation of the previous paragraphs, it is possible to claim that the relationship between design change complexity, use complexity and system viability has yet to be explored empirically and a study addressing these relationships would be useful for organisations seeking to understand how they can design for high variety.

The following section develops the hypothesis for this study.

9.3 Hypothesis development

Considering the discussion in sections 9.2 and 9.2.1, it is possible to make the following observations based upon the existing literature and what we have learnt from the qualitative study.

First, the design change has a direct relationship with system viability as the new resources seek to fill the gap created by variety in use to optimise resource integration for the co-creation of value. However, the effect of low vs. high complexity in design changes has not been empirically explored with respect to its effect on system viability.

Second, whilst the design changes have a direct relationship with system viability, they are moderated by use and its associated complexity. Being moderated by use complexity reflects the customers' ability to integrate and act upon the design changes and use them within their context of use. Simply, the complexity of use moderates the relationship between design change complexity and system viability. This would align with the understanding of function being a surrogate of use.

Based on these observations, it is possible to see one non-design related factor (use complexity) moderating the contribution of one design factor (design change complexity).

It is important to note that section 9.5 specifies the research method as a hierarchical linear regression. This explains the inclusion of hypothesis 1, as the model seeks to add and remove predictor variables to see both their individual and interaction effects on the dependent variable prior to the moderation analysis. The hypothesis for this study can now be presented:

Hypothesis 1: Use complexity positively affects system viability

Hypothesis 2: Design change complexity positively affects system viability

Hypothesis 3: Use complexity moderates the relationship between design change complexity and system viability such that the effects are greater for complex design changes than for simple design changes.

9.4 Data Analysis procedure

This section discusses the data analysis procedure with respect to the unit of analysis, construct definition and measurement, missing data and sample size.

9.4.1 Unit of analysis

Before constructs can be defined, it is important to first outline the unit of analysis for this study.

Firm viability vs use viability.

Traditionally, studies of modularity and firm viability (performance) have focussed on the manufacturing business unit or the product architecture as the basis for their unit of analysis (Salvador et al, 2002; Vickery et al, 2016). This inherently relies on the perspective of one party (i.e., the manufacturer). As highlighted, S-D logic literature has called for greater emphasis on the customers' context of use (e.g., Ng, 2013; Lusch & Vargo, 2014) whilst the servitization literature has called for a re-balance of the literature by exploring phenomenon from the perspective of the customer (e.g., Gronroos & Ravald, 2011; Green et al, 2017) whilst others call for a dual approach (i.e., a balanced approach between provider and customer) (e.g., Tuli et al, 2007; Smith et al, 2014). Thus, a question emerges as to what the relevant approach is for this study. The purpose of this research is to understand design from the perspective of use (high variety) and gain insight into why designing for high variety has different requirements to designing for low variety. In particular, this thesis focusses on the UOR process to do this. Whilst the research focus is on use, organisations still play a significant role in the design change. This implies a balanced view of the phenomenon is appropriate, but emphasis should be placed on outcomes for the customer, given the purpose of design is to optimise value creation and outcomes for the focal beneficiary. As a result, this study concentrates on the effect of design change complexity (organisation focus) on the customers' system viability (i.e., their value creation and outcomes).

Thus, the unit of analysis for this study remains consistent with study one, where both the assets architecture and the customers' context of use both pre and post design change are the focus of the study. The major difference is the nature of the study as this study is quantitative in nature, whereas the first study was qualitative.

9.4.2 Construct definition, measurement items and data collection procedure

This section describes the construct definitions, measurements items and data collection procedure.

9.4.2.1 Independent variable

Within the model in figure 9.1, design change complexity is the independent variable. Modularity theory is one of the most influential theories within product and service design. It assumes that systems can be managed efficiently through the decomposition of a system into smaller, functional chunks referred to as modules that can be developed independently of one another (Schilling, 2000). With specific attention paid to product modularity, organisations can design modules to plug and play into existing architectures assuming that they align with the global design rules of said architecture (Baldwin & Clark, 2000; Brusoni & Prencipe, 2006). In addition, modules can evolve autonomously over time whilst retaining complexity (non-simple interactions) inside the existing module boundaries highlighting that modularity is an efficient strategy for managing a product architecture (Ethiraj & Levinthal, 2004; Pil & Cohen, 2006). However, Henfridsson et al (2014) posit that modularity limits an organisations ability to integrate post-production design changes because the new functionality was not part of the original architecture whilst Yoo (2013) highlights that modularity specifies a specific design hierarchy for each product and that deviating from this design hierarchy, specified early in the design cycle, is not a simple task for the organisation because form and function are bound prior to production. Furthermore, the qualitative study in chapter 8 provided empirical findings to support their claims. The totality of these arguments, combined with the results of the qualitative study, suggest that post-production design changes whose functionality was not part of the original specification, would lead to an increase in design complexity. This means interactions would not be contained within existing module or subsystem boundaries because the interface for the new functionality did not exist. Thus, there would be an increase in the number of non-simple interactions between components emerging outside of the module, where complexity could previously be hidden behind module boundaries, and future design changes would require greater collaboration between subsystem developers as opposed to being able to operate always independently of one another).

We operationalise design change complexity as being high when there is:

"A proportionally higher increase in interactions outside of the modules as compared with those inside the modules"

To measure the construct, we follow the logic of modularity theory. Namely, modularity as described by Baldwin & Clark (2000) specifies that complexity is contained inside a module boundary. For the purpose of this study, complexity is contained inside the subsystem (i.e., the level at which this analysis is conducted). This suggests that any changes to a subsystem should be contained within the existing subsystem boundaries. It is possible to therefore deduce that if interactions outside of subsystems increase at a faster rate than those inside, complexity has not be contained within a module boundary and the complexity of the architecture has increased as a result of the design change. This is because the number of non-simple interactions have spread beyond subsystem boundaries where they can be contained, to outside of the subsystems, which has a number of implications for design and production. Upon review of existing modularity measures (e.g., Mikkola, 2006; Sosa et al, 2007; Voss & Hsuan, 2009), it is determined that none are suitable for this study as they do not directly measure what this construct seeks to represent. Based upon the logic presented here, design change complexity was measured by calculating the interactions outside the existing modules as a proportion of the total interactions in the products architecture and comparing the new version (i.e., once the design change had been integrated) and the old version (i.e., prior to the integration of the change). If the total number of interactions outside the modules as a proportion of total interactions increased from old to new, design change complexity was said to be higher.

9.4.2.2 Dependent variable

Within the model in figure 9.1, system viability is the dependent variable. Traditionally, viability has been seen as synonymous with performance and has often been described with respect to quality, production, supplier, financial or market performance within the OM community (e.g., Williams et al, 1995; Kaynak, 2003; Jacobs et al, 2007; 2011). Within S-D logic, viability is seen as determined by the focal beneficiary during the act of value creation. Green et al (2017) argued that value for the firm is always in the exchange (i.e., financial) because the latter generates valuable revenues for the organisation. Thus, increased revenues and profits would serve as a suitable measure of viability for an organisation. In contrast, value for customers is always in the use and experience, in a way that experience and usage create valuable outcomes for the customer (Ng, 2013). Thus, the authors posit that if we do not assume an overarching transcending notion of value, but discuss it as a construct attributable to an entity as perceived by another (i.e., the value of what and to whom), then value can be described as revenue and profits for the organisation, and the experience and use for the customer. On the postulate that value is attained during use for the customer, it can be assumed that if their outcomes are achieved, the viability of their value creating system will be high. The unit of analysis within this study is the design changes within the customers' context of use where they experience the offering. Thus, it is important that this construct represents value as determined by the customer. Within the interviews, participants were asked the philosophy behind the UORs, with almost all participants responding 'to save lives and prevent casualties'. See appendix 7 for coded items. This suggests that the value of the design changes in use for the customer is that they prevent any more fatalities or injuries during the use of the assets. Given this is the case, this thesis follows a broad definition of system viability as described by the S-D logic literature whereby system viability is defined as:

"A measure of the wellbeing of a focal actor's value creating context with the meaning of wellbeing determined by the focal beneficiary themselves"

In defining system viability as a measure of wellbeing of the focal actor's value creating context, it provides a level of flexibility in measurement items as value creation for one actor may not be the same as another, as noted above.

For this thesis, system viability is operationalised as:

"A performance based measure on the post-integration design change, considering the expected avoidance of fatalities and injuries across severity types"

To measure this construct, the number of fatalities from the Iraq and Afghanistan campaigns were used and weighted against the level of severity of the threat posed that forced the design change. The level of severity was rated on a scale of 1 (not severe) to 5 (very severe) by the platform champions during data collection for the DSMs. In sum, the number of fatalities that occurred in Iraq and Afghanistan during ground military patrols (ground military patrols are those that are conducted on land and assisted by armoured vehicles for either transport or combat fighting purposes) were used as a proxy measure for this construct. Within the dataset, any data point that had information that specifically stated that the fatality occurred whilst not in a vehicle, the data point was removed from the dataset.

Using the responses of interviewees from the qualitative study to help inform the definition and measurement of the construct helps to ensure face validity.

9.4.2.3 Moderating variable

Within the model in figure 9.1, use complexity is the moderating variable. Within the qualitative study, use was defined as a process made up of distinct activities, task and decisions and aligned with the definition provided by Eppinger & Browning (2012). In previous studies of process complexity, Vickery et al (2016) described complexity using an NK metaphor. For them, N referred to the number of components within the product and K the distinct number of processes required to manufacture the product. In contrast to Vickery et al (2016), this study is focussed on the activities and tasks performed by the customer during the use of the organisations value proposition. Therefore, their exact measure of complexity with respect to processes is not directly relevant here, but as noted, Vickery et al (2016) focus more on complicated as opposed to complex in their measurements of product and process modularity. Within the qualitative study, it was found that in the original design specification, there was a perceived scenario of use that consisted of fourteen use activities, and an actual scenario of use that consisted of a larger amount of activities once the UK began their military campaigns in Iraq and Afghanistan. The increase in activities was a result of contextual variety of use that forced the assets to be subjected to things they were not designed for and this increased complexity of use, where interactions are non-simple, non-linear and not necessarily predictable because of emergent interactions between the various elements present during use. It is important to note that the perceived scenario of use was based off the original design specification and the type of military campaign it was originally foreseen these vehicles would be used within (i.e., Eastern European conflicts). Given this, it is possible to tailor the measure of complexity defined by Vickery et al (2016) for the purpose of this study. Here, N refers to the number of activities the asset was originally designed for and K refers to the number of activities the asset was used for post emergence of variety in use within the context of Afghanistan and Iraq. Complexity can therefore be determined and measured as the difference between N and K, where a greater difference refers to a greater level of use complexity as the customer is having to complete a greater number of tasks during value creation.

It is therefore possible to operationalise use complexity as:

"A measure of the complexity of use based upon the number of post-design change activities performed by the customer in use as compared to the number of activities the asset was originally designed for".

Whilst this thesis adapts the measure put forward by Vickery et al (2016), it is argued this measure is more reflective of a complex phenomenon given that the emergence of activities in use is non-linear and unpredictable in reality because of emergence in use. Thus, the interactions and flow between interdependent activities are non-simple and complex.

9.4.2.4 Control variable

The control variable within this study was the platform type. It sought to measure whether there was differences across platform types and whether one platform significantly affected the dependent variable more than the other platforms. Warrior was used as the primary control given it was seen as having significant design changes made to it and was considered a mainstay of the British army during their campaigns in Iraq and Afghanistan.

9.4.3 Data sources

The data for this study was obtained from multiple sources. In addition, the type of data can be seen as objective data. The use of objective data is advocated by the OM community as it allows theory to be constructed out of data based on actual management practice (Benbasat et al, 1987; Voss et al, 2002).

For the design change complexity construct, the data was obtained directly from the product architecture DSMs. Interactions were calculated based upon the number of X marks within the DSM. These were then calculated for the total number of interactions and the total number of interactions outside of modules each time a design change was introduced.

For the use complexity construct, the data was obtained directly from the ASMs. Once the campaign began, the total number of activities was calculated for each platform variant. Following the integration of each design change, the new number of activities were taken away from the number of activities prior to the integration of the design change.

For the system viability construct, data was obtained from three primary locations. The MoD statistics repository, iCasualties.org and Wikipedia (see appendix 1 for links to data sources). Using three different data repositories allowed for greater confidence that the figures represented the phenomenon that was to be measured. In the case that the MoD reports and iCasualties did not match or data was missing, Wikipedia was used as a source to support the data collection to validate either which was correct or fill in any missing data left by the other two sources. However, there was a limitation within the dataset. Whilst it could be observed that the injuries occurred during military patrols that involved land vehicles, it was impossible to conclusively say the injury occurred whilst the customer was operating the organisations asset. However, to minimise this limitation, where information specified that a fatality occurred outside of a vehicle, the data point was removed from the dataset. Thus, caution in the interpretation of the results is given, but given the high proportion of the organisations vehicles used within the customers' context of use as compared to the total number of vehicles and care taken to remove any fatalities that have been confirmed to have not occurred inside of a vehicle, a high level of confidence can be instilled in the results.

With respect to weighting the number of casualties against the severity of the threat, a level of subjectivity on behalf of the platform champions was introduced. A likert scale from 1 (Not very severe) to 5 (very severe) was used to account for the severity of the threat posed to the customer in use that had forced the design change to be commissioned.

The use of objective measures within this study meant concerns surround psychological biases (e.g., recall bias and the halo effect) influence on the results was reduced (Damanpour, 1996; Ketokivi & Schroeder, 2004; Mellat-Parast, 2015).

For this study, there was no missing data in the sample.

9.4.4 Sample Size

The sample size for this study was relatively small. Data was collected between the years 2001-2014. This is based off of the years the UK military was actively involved in the conflicts within Iraq and Afghanistan. As the unit of analysis was the design changes, the sample size was determined by how many design changes were integrated onto each platform variant. In this case, there were sixty design changes, making a sample size of 60. Whilst a small sample, we follow Roscoe’s (1975) rule of thumb, where sample sizes should be 10 or more times the number of variables in the study, therein this thesis effectively requires only 30 samples. As this study has 60, it is deemed a suitable sample size for the model being analysed.

9.5 Research Method

Within this study, a hierarchical linear regression model (HLRM) using IBM SPSS statistical package was performed. HLMRs are a type of statistical regression model that explain whether there is a statistically significant level of variance in the dependent variable after accounting for the other variables within the model (Darlington & Hayes, 2016). Within a HLRM, several regression models are built through the successive addition of other variables to the previous model. In adding to the previous models, scholars are interested in whether the new variables present a significant difference in the $R^{2.}$ (Hayes, 2018). R^2 being the proportion of variance in the dependent variable that can be explained by the model (Fields, 2013). Thus, a number of multiple regression analysis were utilised to first examine the relationship between the single dependent variable (system viability) and the multiple predictor variables (use complexity, design change complexity and the control variable) (Hair et al, 2014) before a HLRM was used to test the moderating effect of use complexity on the design change complexity and system viability relationship.

The choice of a HLRM is based on the following arguments.

First, the goal of this study is to explain the effect of design change complexity on system viability (as determined by the customer), for which a variance based regression model is deemed particularly suited (Fields, 2013). This is because this research is in the early stages of its investigation where the primary concern is establishing potential relationships between the variables as opposed to testing the magnitude of those relationships. Second, this research is concerned with establishing whether use complexity moderates the relationship between design change complexity and system viability. Thus, this research is concerned with adding predictor variables sequentially to see their relationship with the dependent variable in a number of multiple regressions (Hair et al, 2014) before conducting the moderation analysis using a HLRM (Hayes, 2018). This process is commonly associated with HLRMs (Ignatius et al, 2014; Vickery et al, 2016; Hayes, 2018). Third, HLRM is not overly sensitive to small sample sizes (Hayes, 2018). Given this study is only able to access a small sample of objective data from a single organisation, the fact that the modelling technique is not sensitive to this is particularly beneficial. Finally, HLRM are widely used within the OM community and recognised as a suitable statistical technique for models that deal seek to sequentially understand the relationship between the dependent variable and the predictor variables before examining the interaction (moderation) effect of certain variables in the model (e.g., Ignatius et al, 2014; Liu, 2015; Bai et al, 2016; Vickery et al, 2016).

Following justification of the research method, the following section specifies the model.

9.5.1 Model specification

The specification of the model is now presented.

Given the hypothesis that have been generated, it is deemed suitable to present the model as it will be tested given the research methodology. That is, the HLRM mandates four models are created given there are three predictor variables (controls, DCC and UC) analysed first, followed by the moderation analysis. Within these models, DCC refers to design change complexity, UC to use complexity and SV to system viability. The DV is system viability (SV). These are presented in the following figure.

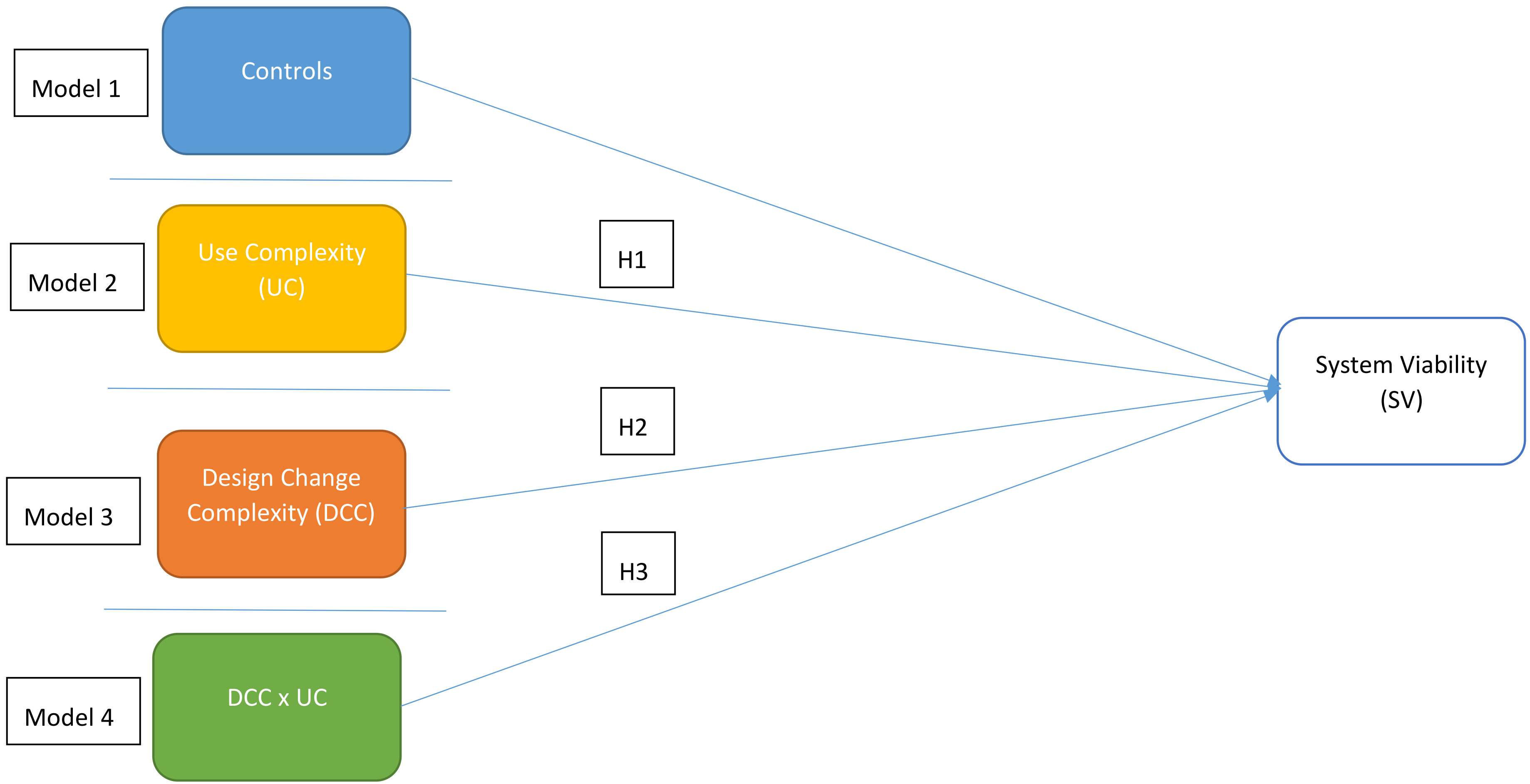

Figure 9.1. Illustration of specified model with hypothesis.

Simply, model one tests the relationship between the controls and the dependent variable (SV). Second, model 2 tests the relationship between use complexity (UC) (predictor variable) and SV. This model tests hypothesis 1. Third, model 3 tests the relationship between design change complexity (DCC) (predictor variable) and SV. This model tests hypothesis 2. Fourth, the HLRM performs a moderation analysis where the relationship between DCC (independent variable) and SV (dependent variable) as moderated by UC (moderating variable) is tested. This model test hypothesis 3.

Statistically, the models are analysed as follows:

Model 1: SV = intercept + a(controls).

Model 2: SV = intercept + a(controls) + b(UC).

Model 3: SV = intercept + a(controls) + b(UC) + c(DCC).

Model 4: SV = intercept + a(controls) + b(UC) + c(DCC) + d(UCxDCC).

The totality of these four models can statistically be represented as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \varepsilon$$

where the B is the Beta coefficient (intercept) and X represents the predictor variables.

It is now possible to present the results of this study.

9.6 Findings

The results of the HLRM are presented in the following table. Please see appendix 8 for full output from the HLRM.

Model		Standardized Coefficients Beta	t	Sig.
1	(Constant)		12.644	.000
	Bulldog 2	-.167	-1.102	.275
	Bulldog 4	-.149	-1.006	.319
	CVR(T) Scimitar	.172	.968	.337
	CVR(T) Spartan	.133	.747	.458
	CVR(T) Samson	.177	.993	.325
2	(Constant)		10.728	.000
	Bulldog 2	-.195	-1.245	.219
	Bulldog 4	-.166	-1.104	.274
	CVR(T) Scimitar	.179	1.001	.322
	CVR(T) Spartan	.160	.879	.383
	CVR(T) Samson	.173	.968	.338
	loguc	.109	.768	.446
3	(Constant)		7.386	.000
	Bulldog 2	-.188	-1.175	.246
	Bulldog 4	-.165	-1.089	.281
	CVR(T) Scimitar	.171	.937	.353
	CVR(T) Spartan	.155	.834	.408
	CVR(T) Samson	.171	.949	.347
	loguc	.099	.665	.509
	logdc	.035	.251	.803
4	(Constant)		9.470	.000
	Bulldog 2	.152	.945	.349
	Bulldog 4	.011	.076	.940
	CVR(T) Scimitar	.457	2.642	.011
	CVR(T) Spartan	.395	2.312	.025
	CVR(T) Samson	.366	2.238	.030
	loguc	-1.951	-3.878	.000
	logdc	-.407	-2.556	.014
	intucdc	2.196	4.214	.000***

Note: *** correlation is significant at the .001 level, ** correlation is significant at the .01 level; * correlation is significant at the .05 level.

Table 9.1. Statistics for models 1 through 4.

Table 9.1 presents the standardised coefficients for models 1 through 4. From table 9.1, it is possible to view both the relative strength of the relationship between the independent and dependent variable and the significance levels. Within the table, we can see the control variables for each model (these are labelled as the names of the vehicles, with warrior labelled as the constant for comparison across the vehicle controls) and the sequential build-up of each variable prior to the final model where the interaction effect is introduced. In table 9.1, we observe no statistically significant results occur for models 2 or 3 where design change complexity and use complexity are analysed. However, model 4 does show a significant result for the interaction between the two variables. This is discussed in greater detail in the following section.

The following table shows a summary of all models with respect to the R-square values.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.355[a]	.126	.045	.59322	.126	1.557
2	.368[b]	.136	.038	.59549	.010	.590
3	.370[c]	.137	.020	.60082	.001	.063
4	.600[d]	.360	.259	.52248	.223	17.762

Table 9.2. Model summaries.

Model 1 shows the control variables have no significant effect on the dependent variable. In presenting a non-significant result, the findings suggest there is no difference in effect size across the different platforms operated by the organisation. This can be concluded from table 9.1 and table 9.2 where no significant result is found.

Model 2 shows use complexity has no significant effect on the dependent variable. This leads the author to reject hypothesis 1. Table 9.1 showed use complexity to have no significant result (p<.446). Table 9.2 shows an R-squared result of .136 that indicates the predictors can explain 13.6% of the variation in the dependent variable.

Model 3 shows design change complexity has no significant effect on the dependent variable. This leads the author to reject hypothesis 2. Table 9.1 showed design change complexity to have no significant result ($p<.803$). Table 9.2 shows an R-squared result of .137 that indicates the predictors can explain 13.7% of the variation in the dependent variable.

Finally, model 4 shows the interaction between design change complexity and use complexity does have a significant result on the dependent variable. This leads the author to support hypothesis 3. Table 9.1 showed the interaction of the two variables to have a significant result ($p<.000$). Table 9.2 shows an R-squared result of .360 that indicates the predictors can explain 36% of the variation in the dependent variable.

The following figure summarises the models in a single figure. The figure presents the sequential nature of the hierarchical regression, showing model 1 as controls, model 2 as use complexity, model 3 as design change complexity and model 4 as testing the interaction effect between use complexity and design change complexity. Accompanying each model is a summary of the significance value and the beta coefficients representing the strength of each predictor variable with the dependent variable. Finally, the R-Squared values are also presented for each model.

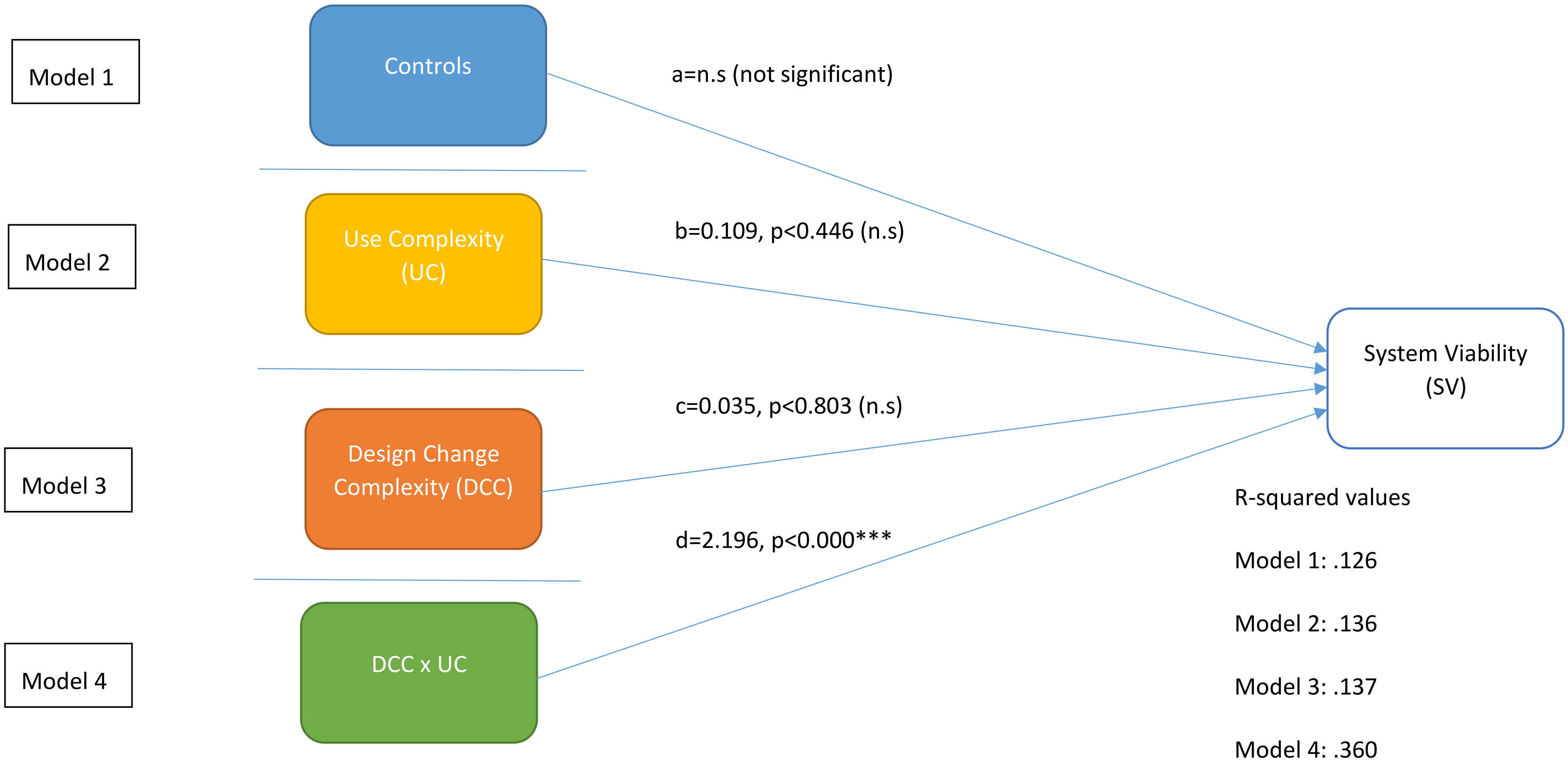

Figure 9.2. Model summaries.

All four models were checked to verify the existence of any violations toward the assumptions made in the HLRM. Notably, no statistical violation was found. The multicollinearity (condition index < 30, VIF < 10, tolerance < 0.1) and the independence error term (Durbin Watson statistic between 1.5 – 2.5) were all found to be within the acceptable statistical limits. The scatter plot containing the regression standardised residual vs. regression standardised predicted value did not show significant patterns, allowing the research to confirm homoscedasticity. Furthermore, the normality assumption was verified from the p-p plot that found all residuals were approximately located along the diagonal line. These tests can be found in appendix 8.

Table 9.3 summarises the hypothesis results for the HLRM.

Hypothesis number	Statement of Hypothesis	Remarks
H1	Use complexity positively affects system viability	Rejected
H2	Design change complexity positively affects system viability	Rejected
H3	Use complexity moderates the relationship between design change complexity and system viability such that the effects are greater for complex design changes than for simple design changes.	Supported

Table 9.3. Summary of hypothesis results.

In addition, this analysis sought to determine more than just the level of association between the predictor variables and the dependent variable. It is designed to show that the form and strength of relationship between the independent and dependent variable varies as a function of another variable (i.e., use complexity). Simply, use complexity is said to modify the strength of the relationship between design change complexity and system viability. This is performed by model 4. The following figure displays the relationship of design change complexity and use complexity with respect to high and low complexity.

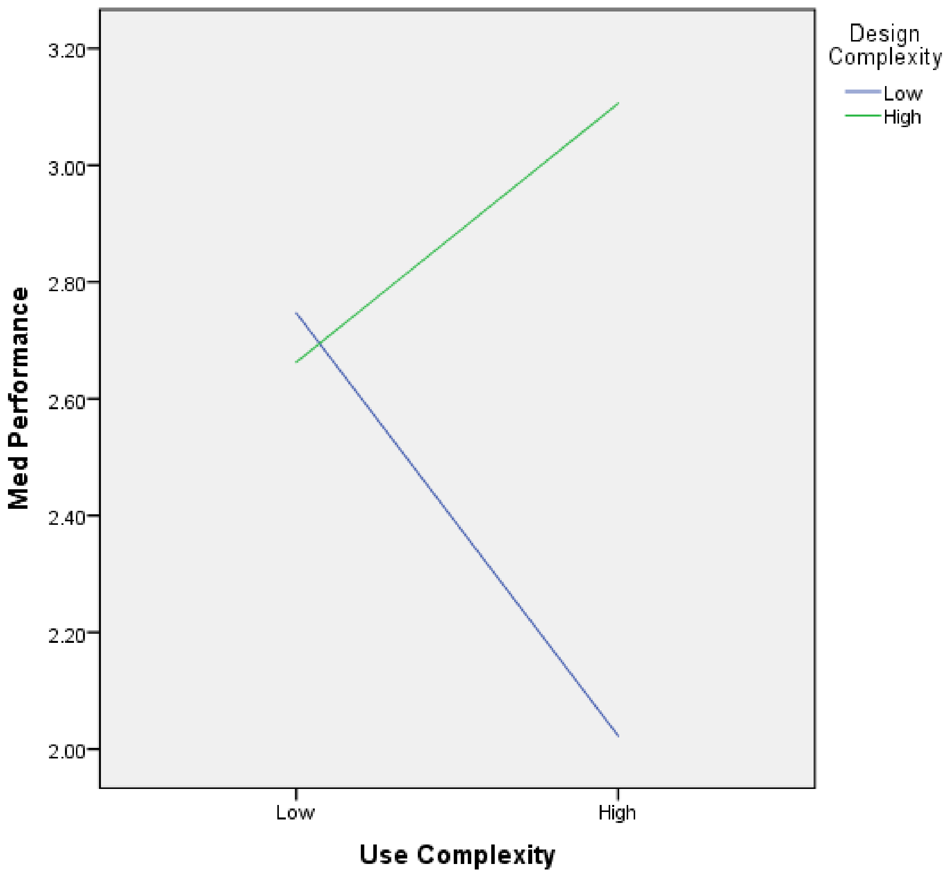

Figure 9.3. Design change complexity and use complexity: their relationship at high vs. low complexity.

This finding suggests that when use complexity is low, a high or low design complexity does not matter. On the other hand, the findings show that as use complexity increases, significant increases in design complexity occur. This suggests design complexity is heighted as use complexity increases.

9.7 Discussion

Study two was designed to explore whether the complexity of the design change and the complexity of use had a relationship with the viability of the customers value creating system. The purpose of this was to gain further insight into designing for high variety. Whilst the first study provided qualitative insight into the negative effect on the organisations value creating systems (i.e., through an increase in through life costs as a result of the design complexity), it was important to understand whether design complexity would also impact the customers' value creating activities and whether use complexity moderated this relationship. Furthermore, the growth gradient analysis presented a relationship between increased design complexity and use complexity (i.e., as design complexity went up, use complexity went down).

Drawing upon the conceptual development in section 9.2, the assumption of the model is that increased design complexity would positively affect system viability. However, the findings showed no significant relationship between the independent variable (DCC) and the dependent variable (SV). However, caution is advised in the interpretation of these results. This is because the qualitative study showed DCC was increased because of limitations in modularity for low variety and that it is the design change, regardless of complexity, that supports the customer in use. This suggests that design complexity does increase when design changes are integrated under the existing designing for low variety frame and design complexity is influenced by use only in that it drives a particular design change that may be high or low in complexity, but, as shown by the results of this study, the complexity of the design changes do not directly affect the outcomes in use. This would go against the argument put forth in the literature and show that the effect of design complexity when deploying a low variety strategy in a high variety context is context dependent and based upon the value of the resource in use. Thus, we can argue that use drives design and organisations, should they wish to viably serve use, need to identify alternate strategies through which to design their offerings and integrate design changes. Similarly, the results found use complexity does not have a significant effect on system viability.

However, a significant result was found when use complexity was analysed as a moderating variable between design change complexity and system viability. The results showed that when use complexity is low, the level of design complexity does not matter. However, when use complexity is high, a higher design complexity is observed but a lower design complexity performs best. However, caution is advised in the interpretation of the results and as noted in the previous paragraph, design change complexity may be result of the limitations in the designing for low variety frame and that the level of complexity in the design change does not ultimately determine its effectiveness in use and rather it is subject to the resources value in use. However, this finding does have a number of implications for the literature and our understanding of designing for high variety and the limitations of the existing designing for low variety frame. First, the results suggest organisations should anticipate a high variety context and account for this during the design of their value proposition in order to avoid an increase in design complexity whilst use exhibits high complexity. Thus, it does not refute the benefits of increasing flexibility in design as described by MacCormack et al (2001), but it does suggest greater emphasis needs to be placed on flexibility post production of the asset so design changes can accommodate the increased variety of use without increasing the complexity of the assets architecture. This supports Verganti & Buganza (2005) who find life cycle flexibility needs to be accounted for by organisations so that modifications post production can easily be achieved. The findings would also support Garud et al (2008) who find complete designs are not suitable for contexts characterised by continuous change. In addition, the findings support Ng & Briscoe (2012) by saying a redesign of the asset can support the viability of the organisation and the absorption of variety in use if the asset is able to be modified, tailored and adapted using 3D printing technology.

In summary, only one significant result was found. Therefore, H1 and H2 were rejected whilst H3 was supported. Whilst caution has been advised in their interpretation, it has been possible to derive some novel insight into the phenomenon. Most notably, it is possible to deduce that design change complexity as moderated by high use complexity significantly effects system viability. With respect to the organisations design strategies, in contexts characterised by continuous change and high variety, it is anticipated an organisation would be best to adopt a designing for high variety frame as opposed to a designing low variety frame, whose limitations have been shown throughout both the first and second studies. Furthermore, if the results of the qualitative study are combined with those found here, it is suggested that a suitable re-design would focus on a hybrid architecture that utilises traditional manufacturing technology for standardisation and 3D printing for variety, where the characteristics of 3D printing allow design change complexity to be minimised when the change is integrated.

Chapter 10: Study Three: The Effect of Use Complexity and Design Change Complexity on System Viability with 3D Printing Implementation

10.1 Introduction

This chapter provides the second quantitative component of the thesis. Drawing upon the literature in chapters 2 and 3 and the findings presented in chapter 8 and 9, the third study of this thesis builds upon the second study to compare the effect of the relationships in the model specified in study two when 3D printing is implemented as compared to traditional manufacturing, which was the subject of investigation in study two. Specifically, it investigates whether the relationships between design change complexity, system viability and use complexity are stronger when 3D printing is used as the manufacturing method.

In similar vein to study two, this study remains exploratory as opposed to explanatory, but does seek to explore a set a hypothesised relationships between (1) *Use Complexity* and *System Viability*. (2) *Design Change Complexity* and *System Viability.* (3) *Design Change Complexity* and *System Viability* moderated by *Use Complexity* when 3D printing is implemented.

This chapter is divided into six further sections. First, section 10.2 presents the conceptual development of the quantitative model. Second, section 10.3 presents the hypothesis to be tested within this study. Third, section 10.4 presents the data analysis procedure that includes the unit of analysis, construct definition and measurement items, data sources and sample size. Section 10.5 presents the research method and specification of the model.

Fifth, section 10.6 presents the findings of this study. Finally, section 10.7 presents the discussion of this study and compares and contrasts the results against the existing literature before summarising the main contributions of this chapter.

10.2 Conceptual development

As detailed in chapter 6, the specific research question for this study is:

Does design change complexity affect system viability greater under a higher use complexity post 3D printing implementation as compared to traditional manufacturing?

To support the quantitative research, it is important to start from the literature and the previous two studies.

Within the first study, 3D printing was found to be an enabler of designing for high variety as it could allow the rapid production of components to support the latent needs of the customer in use. Thus, 3D printing is doing to manufacturing what digital has done to music, books and apps (Ihl & Piller, 2016). However, study two focussed on traditional manufacturing technology, which is assumed to have significant delays in delivery of the resources. This means the customer has to cope with sub optimal resources for a greater period of time. Traditional manufacturing also limits the amount of design changes they can make given the cost of traditional manufacturing and the difficulty organisations have in integrating these changes. This was highlighted in studies one and two. From both the literature and study one, evidence suggests that 3D printing has a faster response rate to conditions in the environment (Holmstrom et al, 2010; Holmstrom & Partanen, 2014; Ihl & Piller, 2016). Hence, changes and adaptations to a product would be addressed within a shorter time frame than otherwise would have been prolonged under a traditional manufacturing product rework or reconfiguration (Holmstrom & Partanen, 2014). In addition, it is also reasonable to suggest that the number of changes to be made would be increasingly smaller as 3D printing could provide design change interventions at a more frequent interval. In other words, unintended use of the asset will not escalate to a proportion that is unmanageable before changes can take place via 3D printing, which delays the binding of form and function until the latent needs of the customer arise in use (Ng, 2013). This would allow organisations to focus on product instances and modify, tailor and adapt the asset on a mission by mission basis (Holmstrom & Partenan, 2014) as also acknowledged by practice with the CDE in study one and the DoD in chapter 1. Furthermore, the findings of study one highlighted 3D printing could enable the rapid 'rerolling' (i.e., reconfiguration) of assets based upon sticky information provided by the customers in use, with rerolling a military term used to represent the (re)configuration of an asset for a particular mission or task. Combining this discussion with the unique characteristics of geometric freedom and digital materiality associated with 3D printing (Ng, 2013; Petrick & Simpson, 2013; Huang et al, 2013) also means that the ratio of changes outside of module to the total will be smaller post 3D printing implementation as compared to traditional manufacturing. However, to obtain this benefit the findings from study one suggested it would require engineering capabilities of a new order, with multiple respondents suggesting a hybrid architecture between traditional manufacturing and 3D printing for variety absorption.

Thus, the totality of the argument is that in existing settings, such as those in study one and two, complexity in both design and use would exist and increase in certain instances. In design, it increases when a design change is implemented onto a platform that has been designed using a low variety frame and traditional manufacturing technology has been used. For use, complexity increases the longer the customer waits for a design change to be integrated. However, once a design change has been integrated use complexity does go down (i.e., when a design change is integrated, the number of additional activities in use drops as shown on the growth gradient analysis in chapter 9). Thus, when using traditional manufacturing technology, there is a relationship between design change complexity increasing and use complexity reducing. Furthermore, the time it takes to design, manufacture and integrate the new resources means the customer is without the optimal resources for a significant period of time. With 3D printing, the argument put forth in this section suggests both would improve following its implementation and the subsequent effects on system viability would also be improved. For design, this is because 3D printing has affordances closer to digital technology that enable geometric and design freedom as well as economies of one. Things traditional manufacturing does not afford. Second, for use, 3D printing can integrate resources faster and thus the customer is not without appropriate resources for a significant period of time.

Based upon this argument, this study builds upon the research conducted in chapter 9 and uses the same dataset to conduct a bias corrected bootstrap sample to show the effect of 3D printing on variety absorption in use. On the assumption that 3D printing can allow resources to be integrated at more regular intervals, a bootstrap sample was used to resample from the existing dataset. It is important to note that because bootstrapping takes a random sample with replacement from the existing dataset, the estimates that will be arrived at each time will be slightly different (Miles, 2013). That said, bootstrapping allowed a larger dataset to be generated to reflect the integration of resources at more regular intervals i.e., the same timeframe was used as the study in chapter 9, but a larger sample generated from the bootstrap method means more resources were integrated more often within that time frame. Certain assumptions around the effect of more regular integration of resources on use complexity is discussed later in the chapter. Unfortunately, the dataset does not allow for design change complexity to be manipulated and simulated and thus we cannot quantitatively show that design change complexity would reduce as a result of 3D printing, as argued in the conceptual development. However, we can infer this would be the case from the literature and the qualitative study.

10.3 Hypothesis development

Given this study investigates the same model as the second study with the addition of the implementation of 3D printing within this model, it is possible to modify the hypothesis presented in chapter 9 to accommodate this difference. Therefore, the hypothesis for this study are as follows:

Hypothesis 1: Use complexity positively affects system viability with 3D printing implementation.

Hypothesis 2: Design change complexity positively affects system viability with 3D printing implementation.

Hypothesis 3: Use complexity moderates the relationship between design change complexity and system viability such that the effects are greater for complex design changes than for simple design changes with 3D printing implementation.

10.4 Data analysis procedure

The data analysis procedure with respect to the unit of analysis is again the same unit of analysis as study two. The reader is therefore referred to section 10.4.1 for the unit of analysis of this study. The major difference is the sample size to account for the 3D printing component. This is now discussed.

Based on the conceptual development in section 10.2, this study sought to manipulate the dataset such that it represented the phenomenon post 3D printing implementation. Based on this and given that the period of observation of the dataset is 14 years with 60 design changes that had been implemented, this study assumes that with 3D printing, the number of design changes would have been increased by 4-fold. This is supported by both the literature and results from study one, where it was argued that 3D printing would allow design changes to occur on a mission by mission basis dependent upon the customers' requirements in use. Notably, the documentary data found that missions took place on a daily basis and were conducted by multiple battalions of the British army, thus multiple missions took place on a single day during the conflict period. Therefore, it is possible to suggest 4-fold is a conservative number, but one that is seemingly more realistic than a design change every single mission. Based upon these assumptions, this study sets the condition that in the case of 3D implementation, the use complexity with more than 2 or more additional activities would have been attended when use complexity registered a value of 1. As an example, within the data, before a design change is implemented, we observe a use complexity value of 4 (there are 4 additional activities conducted by the customer as compared with what the perceived scenario of use was) and the time between the increase in use complexity and the design change being implemented was two years. On the understanding that 3D printing can be integrated faster, we make the assumption that use complexity would not be left to increase exponentially as the variety in use could be attenuated at a much faster rate than when traditional manufacturing is used. Thus, in the example provided, we will set use complexity to 1, as opposed to 4. This process was repeated for all use complexity values above 1. This implies that the number of additional activities an individual needs to perform to complete their task as compared with the number of tasks the product was designed to participate in would potentially not exceed 1 before 3D printing intervenes, which compared to traditional manufacturing is almost instant. In this context, the assumption is the organisation has adopted a designing for high variety strategy and emphasis has been placed on the provision of multiple different design files that can be printed and integrated by the customer. Thus, their strategy is proactive as compared to reactive in this instance. This means the time for the design to be created, manufactured, assembled and used is significantly reduced as the organisation has already designed a wide range of digital resources that could potentially satisfy the customers' use context and 3D printing speeds up the other three elements of production, installation and use.

Therefore, in our additional 240 samples (60 x 4), this study maintains all other measures and values while the values of use complexity of more than 2 were set to 1. Hence, this thesis combined this dataset with the original 60 design changes and performs a bias corrected bootstrapping method with 1000 samples. This study uses bootstrapping to derive robust estimates of standard errors and confidence intervals because the system viability and design complexity values can be varied for those design changes with values of use complexity that were fixed to 1.

10.5 Research method

The primary research method for this chapter was a hierarchical linear regression and follows the same procedures to the study in chapter 9 (see section 9.5), the major difference was the addition of bootstrapping detailed in the previous section. Therefore, the model specification is also the same and not repeated here. Please refer to section 9.5.1 for model specification.

10.6 Findings

The results of the HLRM are presented in the following table. Please see appendix 8 for full output from the HLRM.

		Beta Coefficient	Bootstrap[a]				
			Bias	Standard Error	Significance (1 Tailed)	BCa 95% Confidence Interval	
						Lower	Upper
1	(Constant)	2.500	-.003	.098	.000***	2.304	2.686
	D1	-.365	.006	.124	.002**	-.622	-.084
	D2	-.359	.006	.132	.003**	-.619	-.091
	D3	.245	.000	.119	.020*	.017	.462
	D4	.189	.000	.123	.060	-.064	.443
	D5	.252	.001	.121	.022*	.013	.484
2	(Constant)	2.522	-.002	.107	.000***	2.302	2.721
	D1	-.348	.009	.126	.003**	-.605	-.073
	D2	-.343	.008	.133	.004**	-.616	-.054
	D3	.247	.001	.119	.019*	.014	.480
	D4	.183	.000	.122	.066	-.069	.436
	D5	.256	.002	.122	.019*	.014	.494
	loguc	-.105	-.010	.195	.243	-.507	.251
3	(Constant)	2.408	-.007	.167	.000***	2.019	2.706
	D1	-.327	.009	.133	.008**	-.598	-.036

	D2	-.343	.008	.133	.004**	-.613	-.056
	D3	.229	.002	.118	.028*	-.009	.469
	D4	.172	.001	.123	.077	-.080	.428
	D5	.252	.001	.124	.024*	.013	.492
	loguc	-.132	-.006	.205	.268	-.544	.252
	logdc	.546	.012	.550	.161	-.509	1.664
4	(Constant)	2.953	.004	.125	.000***	2.647	3.191
	D1	.142	.005	.109	.094	-.078	.374
	D2	-.046	.006	.102	.327	-.254	.171
	D3	.518	.001	.098	.000***	.315	.700
	D4	.436	.002	.098	.000***	.239	.634
	D5	.438	.002	.097	.000***	.231	.639
	loguc	-5.097	-.035	.466	.000***	-6.067	-4.198
	logdc	-2.533	-.035	.592	.000***	-3.700	-1.485
	intucdc	19.896	.155	1.945	.000***	16.089	24.223

a. Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Note: *** correlation is significant at the .001 level, ** correlation is significant at the .01 level; * correlation is significant at the .05 level.

Table 10.1. Bootstrap for coefficients for study three.

Table 10.1 presents the standardised coefficients for models 1 through 4. From table 10.1, it is possible to view both the relative strength of the relationship between the independent and dependent variable and the significance levels. Within table 10.1, the D1-D5 relate to the dummy (control) variables, which in this study are consistent with the previous study; the organisation's vehicles. In line with study two in chapter 9, we witness similar results with respect to significance levels even after the bootstrap has been conducted. The significance values for both models 2 (use complexity) and 3 (design complexity) remain non-significant whilst the interaction effect again returns a significant result. On the right hand side of the table, the confidence intervals are presented. The confidence intervals use the parameter estimates created by the bootstrap sample to work out the limits within which 9% of these estimates fall. The results of the confidence intervals allow this research to be confident the interval bounded by the true population parameter (in this case leaning toward 95%) is accurate and representative of the sample population should this bootstrap procedure be repeated multiple times.

The following table presents the summary of the model with respect the R-squared values for all four models.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.355[a]	.126	.111	.568	.126	8.477
2	.356[b]	.127	.109	.569	.001	.341
3	.362[c]	.131	.110	.568	.004	1.302
4	.552[d]	.305	.286	.509	.174	73.022

Table 10.2. Model summary for study three.

Model 1 shows the control variables have no significant effect on the dependent variable. In presenting a non-significant result, the findings suggest there is no difference in effect size across the different platforms operated by the organisation. This can be concluded from table 10.1 and table 10.2, where the findings show no significant results.

Model 2 shows use complexity has no significant effect on the dependent variable when 3D printing is implemented. This leads the author to reject hypothesis 1. Table 10.1 showed use complexity to have no significant result ($p<.243$). Table 10.2 shows an R-squared result of .127 that indicates the predictors can explain 12.7% of the variation in the dependent variable.

Model 3 shows design change complexity has no significant effect on the dependent variable when 3D printing is implemented. This leads the author to reject hypothesis 2. Table 10.1 showed design change complexity to have no significant result ($p<.550$). Table

10.2 shows an R-squared result of .131 that indicates the predictors can explain 13.1% of the variation in the dependent variable.

With both of the previous results for models 2 and 3, whilst no significant results were found it is worth noting the values were closer to statistical significance when 3D printing is introduced as opposed to 3D printing not being introduced (i.e., comparing study three with study two).

Finally, model 4 shows the interaction between design change complexity and use complexity does have a significant result on the dependent variable. This leads the author to support hypothesis 3. Table 9.1 showed the interaction of the two variables to have a significant result ($p<.000$). Table 10.2 shows an R-squared result of .305 that indicates the predictors can explain 30.5% of the variation in the dependent variable.

The following figure summarises the three models in a single figure. This figure shows the models that were sequentially built to complete the analysis. Model 1 to 3 shows the predictors effect on the dependent variable whilst model 4 shows the interaction effect between DCC and UC. Accompanying each model is their beta coefficient and significance value. In line with the descriptions above, online model 4 has a significant result. It is important to note that the beta coefficient will usually be large for the interaction effect as it is a multiplication of two predictor variables. Finally, the figure presents the R-squared values for each of the models. As in the descriptions above, only model 4 has a R-squared value that explains a sufficient amount of variation in the model (30.5%).

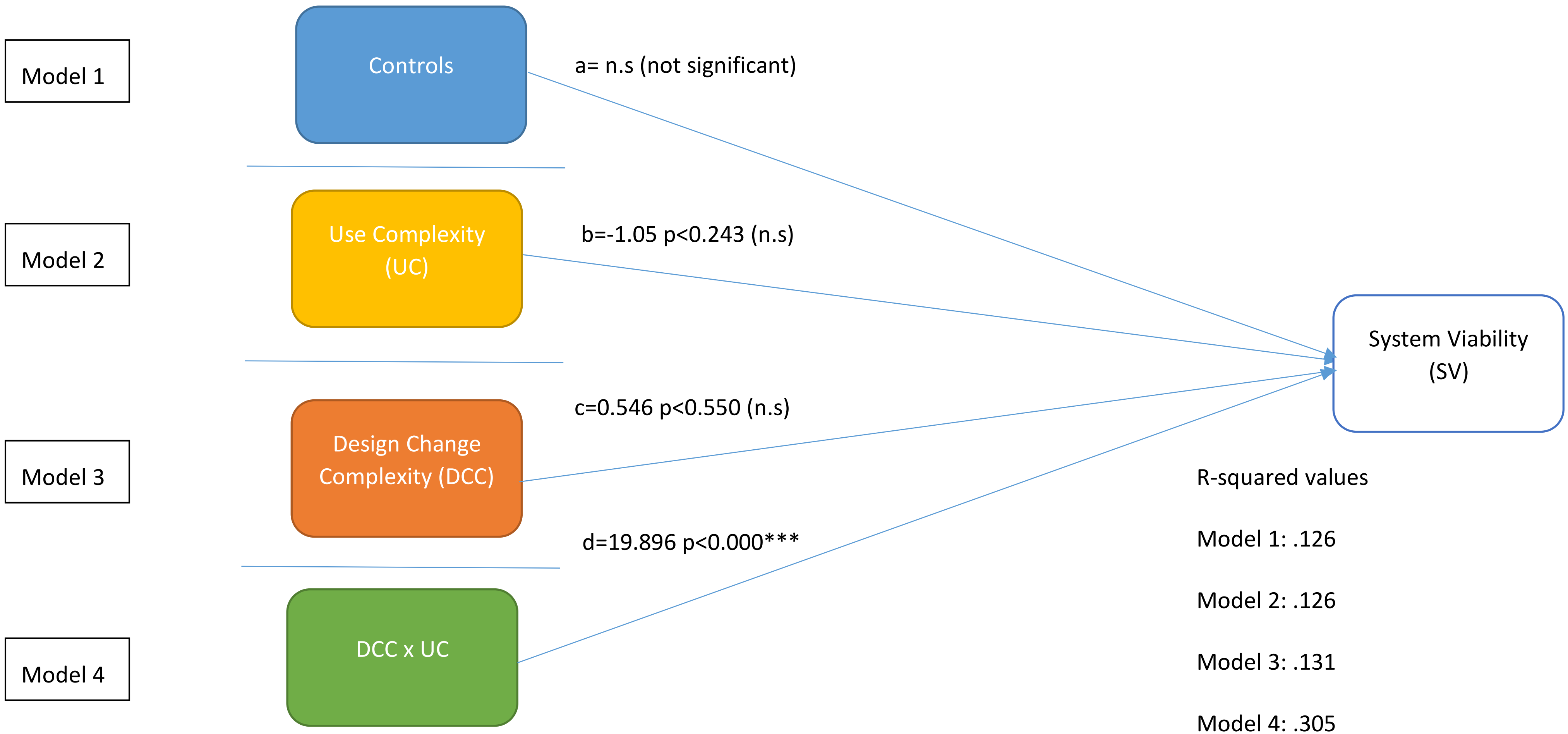

Figure 10.1. Results of the HLRM for study three.

All four models were checked to verify the existence of any violations toward the assumptions made in the HLRM. Notably, no statistical violation was found. The multicollinearity (condition index < 30, VIF < 10, tolerance < 0.1) and the independence error term (Durbin Watson statistic between 1.5 – 2.5) were all found to be within the acceptable statistical limits. The scatter plot containing the regression standardised residual vs. regression standardised predicted value did not show significant patterns, allowing the research to confirm homoscedasticity. Furthermore, the normality assumption was verified from the p-p plot that found all residuals were approximately located along the diagonal line. These tests can be found in appendix 9.

The following table summarises the hypothesis results for this study.

Hypothesis number	Statement of Hypothesis	Remarks
H1	Use complexity positively affects system viability with 3D printing implementation.	Rejected
H2	Design change complexity positively affects system viability with 3D printing implementation.	Rejected
H3	Use complexity moderates the relationship between design change complexity and system viability such that the effects are greater for complex design changes than for simple design changes with 3D printing implementation.	Supported

Table 10.3. Summary of hypothesis results for study three.

In addition, this analysis sought to determine more than just the level of association between the predictor variables and the dependent variable. It is designed to show that the form and strength of relationship between the independent and dependent variable varies as a function of another variable (i.e., use complexity) after the implementation of 3D printing (i.e., as compared to the previous study). Simply, use complexity is said to modify the strength of the relationship between design change complexity and system viability post implementation of 3D printing. This is performed by model 4. The following figure displays the relationship of design change complexity and use complexity with respect to high and low complexity.

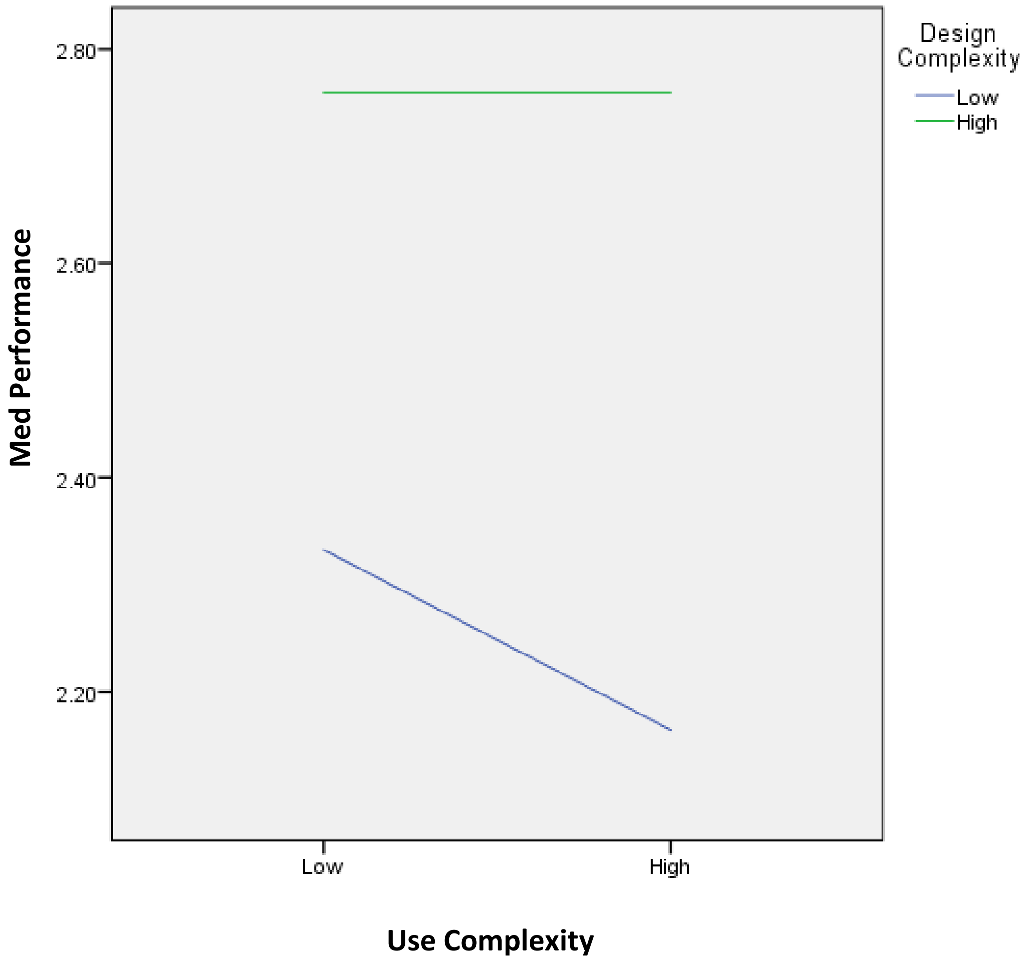

Figure 10.2. Design change complexity and use complexity: their relationship at high vs. low complexity post implementation of 3D printing.

This finding suggests that when use complexity is low or high, a low design complexity performs best when 3D printing is implemented as compared with traditional manufacturing as in figure 9.3. For example, for low design complexity (in both high and low use complexity scenarios), the 3D printing simulation (figure 10.2) has a median value for system viability between 2.15 and 2.35. In contrast, for traditional manufacturing in figure 9.3, low design change complexity has values ranging between 2.10 and 2.80. This reflects the interpretation that with the implementation of 3D printing, organisations will improve system viability more than if they use traditional manufacturing techniques. However, the difference between the two technologies for a high design complexity is negligible. The only notable difference is that for traditional manufacturing in figure 9.3, the effect of design change complexity across a high and low use complexity does differ whereas for 3D printing it does not. However, the differences between the median scores for systems viability is minimal and only made to look significantly different because of the axis on the graph, which leads the authors to interpret the results as having a negligible difference when assessing the effect of high design change complexity on system viability.

10.7 Discussion

Study three was designed to explore whether the complexity of the design change and the complexity of use had a relationship with the viability of the customers value creating system when 3D printing was implemented. The purpose of this was to gain further insight into designing for high variety when supported by 3D printing. Whilst the second study showed the results for traditional manufacturing, the literature and study one suggested that 3D printing would be able to improve the results given its unique characteristics and digital materiality. In this case, the study focussed on how 3D printing would allow customers' to respond to variety on a mission by mission basis, with a conservative number of two design changes per month applied to the data set to respond to said variety. As outlined in the data analysis section, mission by mission could mean every single day based upon the documentary data viewed for study one, meaning the amount of changes analysed in this study are conservative, yet realistic within practice.

As in study two, the findings showed no significant relationship between the independent variable (DCC) and the dependent variable (SV) nor did the results find use complexity to have a significant effect on system viability.

The final model did find a significant result however and this is a consistent finding with the previous study. The results of the hierarchical regression analyses on the 60 samples, 300 samples and the 1000 bootstrapped samples are similar such that use complexity and design change complexity have no direct impact on system viability, but their combined interaction effect possess an effect on the latter (model 4). The results showed that when use complexity is low or high, the lower design complexity performs better following 3D printing implementation. Furthermore, when compared to traditional manufacturing in figure 9.3, it can be seen that 3D printing performs roughly the same for low design change complexity and high use complexity but performs better for low design change complexity and low use complexity. Thus, 3D printing has more significant effects under certain conditions than traditional manufacturing. This is an interesting finding and provides conditions for organisations to use to inform their design and operations decisions when developing and implementing a design for high variety strategy. Namely, the increased amount of design changes suggests organisation will need to re-evaluate their through life design flexibility to accommodate design changes post production. It is also possible to infer that organisations will need to place greater emphasis on upstream design activities so that they can efficiently provide a range of novel solutions for the customer to print at the point of use. This brings to the fore three primary contributions. First, Verganti & Buganza (2005) studied through life flexibility within the context of internet services, this study finds similar conclusions with the addition that manufacturing organisations will need to focus on both traditional manufacturing and digital manufacturing given the type of offering they provide. Based on the results presented here and within study one, it is anticipated that this would require significantly different engineering principles and operations practices to those put forth by Verganti & Buganza (2005) and those currently prevalent within practice. Second, the findings both align and contribute to the discussion presented by Ng (2013) and Green et al (2017). Within their studies, they found a S-D logic view of servitization would require an organisation to understand where to design the boundary between scalability (the physical asset) and variety absorption (human resources). The results within this study found that this boundary can be designed within the physical asset itself, given 3D printing allows the asset to be re-designed such that it can accommodate variety without the need for human resource intervention that has long been used by organisations to absorb variety (Ng & Briscoe, 2012). Furthermore, the findings explicitly show which design changes would benefit system viability the most when use complexity (i.e., variety) is high or low, meaning the case organisation can design the boundary with greater confidence that where they are creating variety with 3D printing will have the most significant effect on the customers value creating activities. Furthermore, in finding that organisations can design the boundary for variety and scalability within the asset itself suggests product instances aligns closer to a layered modular architecture than a standard modular architecture. However, layered modular architectures have primarily been studied within the context of digital artefacts, where scalability is created by a standard material offering and variety is created by a digital layer (i.e., apps). Whilst outside the scope of this study, it is interesting to note this transition in an industry characterised by heavy industrial goods as opposed to small, consumer objects where the layered modular architecture has primarily been studied (Yoo et al, 2010; Yoo, 2013; Lusch & Nambisan, 2015). This finding would support Maull et al

(2015) who find digitisation is effecting even those industries characterised primarily material assets. Thus, this finding contributes to the literature by opening up a new area of enquiry in the pursuit of product instances in a servitized context and that is in understanding the design principles of a layered modular architecture for 3D printed components designed to absorb variety in use. This duality of 3D printing as a material asset characterised by digital materiality possess a number of new challenges not previously faced by operations management.

However, caution in the interpretation and generalisation of these results is given as the case studied is a single organisation in a particular conflict zone and whilst relevant to the case organisation within this conflict, the results may not be generalizable to other organisations or even other conflict zones based on these results alone. Multiple cases would allow the results to be cross-analysed and a more informed decision around the use of 3D printing across different contexts would be possible to derive. This would align with propositions put forward by Eisenhardt (1989). That said, the results do provide one of the first empirical investigation into the use of 3D printing to focus on product instances and the customers' context of use. This leads to the final contribution whereby the study addresses the call from Holmstrom & Partanen (2014) to empirically investigate the use of 3D printing within a servitized context. In doing so, it has presented particular conditions under which 3D printing for resource (re)configuration would be most beneficial for both the customer and the organisation.

In summary, only one significant result was found. Therefore, H1 and H2 were rejected whilst H3 was supported. Whilst caution has been advised in their interpretation, it has been possible to derive some novel insight into the phenomenon. Most notably, it is possible to deduce that 3D printing, in certain instances, performs better than traditional manufacturing. In study two, it was argued that in contexts characterised by high variety (i.e., high use complexity), organisations need to re-design the physical asset to be able to absorb variety in use as opposed to relying on human resources that are inherently difficult to scale and replicate. Within this study, it shows how 3D printing, where form and function is not bound until the latent needs arises in use, can be used to offset some of the limitations of traditional manufacturing technology and support customers in better co-creating value. Following the conceptual development and the results presented in figure 10.1 and 10.2, it is found that a number of benefits emerge from the following benefits and characteristics associated with 3D printing. First, it can be deployed at the point of use. Second, the technology allows the binding of form and function to be delayed almost permanently. Third, because the number of changes to be made would be increasingly smaller as 3D printing could provide design change interventions at a more frequent interval. In other words, unintended use of design will not escalate to a proportion that is unmanaged before changes can take place. Thus, 3D printing provides the organisation the opportunity to serve use efficiently and effectively via the re-design of the physical asset to accommodate variety through the addition of 3D printing technology. Based upon the results, it is possible to suggest that in the context of this study, organisations are best adopting 3D printing for low complexity design changes to serve both high and low use complexity.

Chapter 11: Converging on a conceptual framework for designing for high variety and modularity in context

Drawing on the results of all three studies, it is possible to converge on a conceptual framework that seeks to explain what factors positively or negatively effect an organisations ability to design for high variety (i.e., modularise the customers' context of use for efficient and effective resource integration). Based on the results of study one, two and three, it is possible to identify seven factors relevant to designing for high variety and the modularisation of the contextual experience for efficient and effective resource integration; actor agency, value proposition design, digital technology, design rules (institutions), heterogeneity of resources, urgency and contextual variety. The framework is presented in figure 11.1.

The findings presented in each of the studies constitutes a contribution toward a mid-range theory in S-D logic, as it shows the application of the logic's principles renders not only a fundamentally different conceptualisation of design, but it also alters the focus of the organisation from efficiency in production to effectiveness in use. Based on the findings, it concurs with Vargo & Lusch (2016) who argue that the primary implications of S-D logic are strategic and enabled via innovative insight. Moreover, this research finds support for FP3 that states goods are a distribution mechanism for service provision and FP9 that states all actors are resource integrators and FP11 that states actors are guided by actor generated institutions. As discussed, designing for high variety acknowledges the benefits of a physical asset as a distribution method for service and presents a number of results that show its (re)configuration provides a better service for the customer in use and if redesigned to absorb variety, could support the viability of the entire service ecosystem. Second, by presenting designing for high variety as a process of resource integration, it provides empirical support for FP9 within the context of servitization. Finally, by highlighting the increasingly important role of institutions and actor agency in designing for high variety as in study one, this thesis finds a number of propositions that substantiate the claims by Edvardsson & Tronvoll (2013), Edvardsson et al (2014) and Vargo & Lusch (2016). The findings show how institutions of the focal beneficiary need to be accounted for when designing and proposing a new offering to satisfy their latent needs in use. Furthermore, within the context of design it supports Edvardsson & Tronvoll (2013) in that designing for 'resource configurations' is more important than focussing on individual functional and aesthetic attributes of individual resources. The concept of 'resource configurations' aligns with the notion of product instances. Taken together, the findings show that use and value creation drive design. Based upon these results, it is easy to draw parallels with these findings and those put forward in the S-D logic literature. As proposed by Brodie et al (2011), mid-range theory serves as a bridge between empirical findings and general theory. The findings presented here have been shown to do this through the development of a number of propositions associated with S-D logic that can be empirically tested in future research which may ultimately support, verify or modify the findings presented within this study. Finally, drawing upon the modularity literature (Schilling, 2000), the servitization literature (Ng & Nurudupati, 2010; Ng & Briscoe, 2012; Smith et al, 2014; Green et al, 2017), the S-D logic literature (Vargo & Lusch, 2004; 2016; Lusch & Nambisan, 2015) and the design literature (Garud et al, 2008; Kimbell, 2011; Manzini, 2011) and the results and discussion of the three studies, it is possible to derive a framework that illustrates the factors relevant to designing for high variety and the modularisation of a customers' contextual experience for the efficient and effective integration of resources where organisations support product instances as opposed to product types. Within the framework presented in figure 11.1 are seven factors that contribute toward the successful design of an offering focussed on high variety and the modularisation of use. In line with Schilling (2000), a number of factors are seen to either positively or negatively affect whether a system, in this case the contextual experience, would shift toward or away from a more modular state. Based on the literature review and the results contained within the study, it is possible to breakdown the model into three distinct portions. First, the value proposition design is separated from the four factors contained within the box. This factor focusses on the organisations capabilities and the design of their value proposition. Notably, this is influenced by three of the factors contained within the box and these factors are driven by use and are context specific. These are actor agency, design rules (institutions) and the heterogeneity of resources available in use. These inform the value proposition design as it helps the organisation understand where to draw the boundary between standardisation and variety, with variety provided by 3D printing in use. Thus, the four factors contained within the box are the four primary components of use that need to be understood by the organisation if they are to design an efficient and effective value proposition that successfully allows them to create thin crossing points within the contextual experience so that they can efficiently and effectively integrate resources for the benefit of the customer. This corresponds with an outside-in approach presented by Payne et al (2008). The contextual experience moving toward a modular state is indicated by the positive signs from each of the four factors directly influencing the contextual experience. Should we wish to understand what shifts a contextual experience away from a modular state, we would reverse the symbols. Urgency and contextual variety are two constructs that can negatively affect the organisation and the customer in the process of resource integration. This can be for a number of reasons with one simple example being the actor no longer has the agency in use to integrate resources and co-create value under the conditions which have emerged from the variety of the use context. Evidence supporting the influence of these factors were found within study one. However, should the organisation create a suitable boundary between variety and standardisation, it is possible the effects of contextual variety and urgency can be offset by the design of the value proposition presented by the organisation, as shown in study three. However, as noted in study one and three, this requires the organisation to move toward a layered modular architecture and develop engineering knowledge of a new order. Namely, it is suggested the organisation needs to focus on hybrid architecture of traditionally manufactured and digitally manufactured components.

Taken together, this framework provides one of the first contributions toward understanding designing for high variety and modularity in context. It brings to the fore the important role of different factors such as actor agency and design rules in the design process and it extends the discussion by Spring & Araujo (2009) that finds the identification and creation of thin crossing points is one of the most important roles for operations managers in the future, especially with advances in technology allowing new thin crossing points to emerge within the contextual experience. Furthermore, this framework addresses calls from Ng (2013) who specifically called on the research community to empirically investigate and derive a greater understanding of designing for high variety and modularity in context from a S-D logic lens. Finally, in similar vein to Schilling (2000) and Schilling & Paparone (2005), the author acknowledges that the framework may not be perfect and has yet to be empirically scrutinised. However, if future development and empirical scrutiny modifies the framework, we will have provided a novel foundation for a greater understanding of designing for high variety and how we can create thin crossing points within the customer's use context. If this occurs, this would allow organisations to efficiently and effectively integrate resources to satisfy latent needs and co-create value with the customer and this initial framework will have served its purpose.

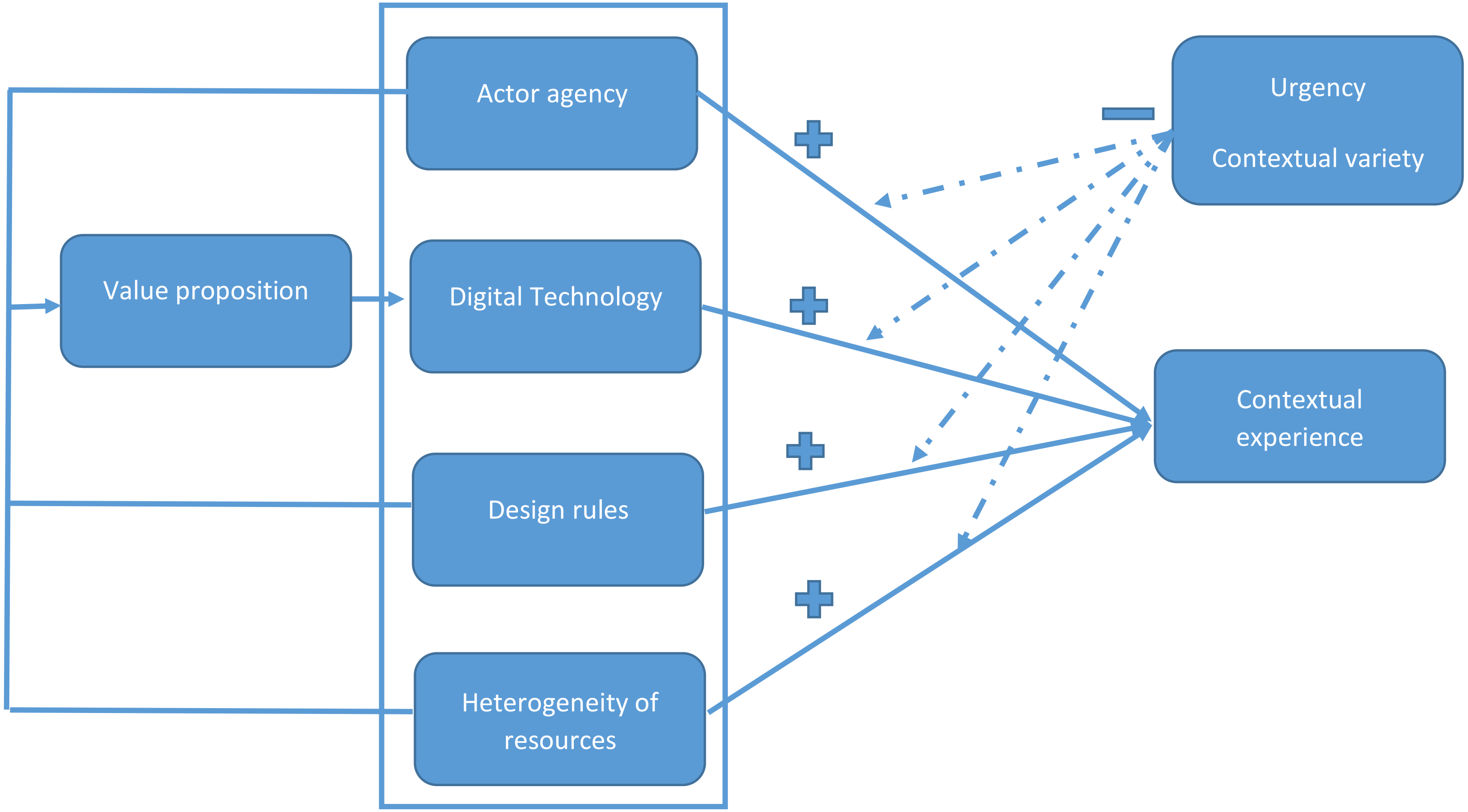

Figure 11.1. Conceptual Framework illustrating modularity in context.

Chapter 12: Conclusions, Limitations and Future Research Opportunities

12.1 Introduction

In this final chapter, the different strands of research discussed throughout this thesis are brought together, the three studies are discussed, some answers for the question 'why does designing for high variety have different requirements to designing for low variety?' are given before the contribution to knowledge is summarised in number of succinct points. The thesis concludes with an appreciation of the managerial implications, limitations and future research opportunities.

12.2 Conclusions

12.2.1 Literature review

Throughout the literature review, it was clear two separate design strategies were emerging; designing for low variety and high variety. Whilst designing for low variety was relatively well established and illustrated using examples from modularity theory in the design of products and services, later labelled modularity for low variety, it was found that designing for high variety was significantly lacking in any robust theoretical foundation. What was clear was that advances in digital technologies and the convergence on value being created in use and experience was driving the research community toward designing for high variety where emphasis was placed on the entanglement of design and context (i.e., the customers' context of use). Whilst resource integration was found to underpin the concept, it was found to be theoretically underdeveloped. To gain insight into resource integration, this thesis drew upon S-D logic and modularity theory as defined by Baldwin (2008).

As a result of the literature review, it was concluded that modularity theory, as described by Baldwin (2008), aligned with the concept of designing for high variety and provided a more relevant theoretical insight when coupled with S-D logic. Furthermore, it aligned well with the OM community who were recognising the importance of a broader understanding of modularity theory (e.g., Spring & Araujo, 2009). However, it was recognised that modularity in its present form did not provide significant theoretical insights into designing for high variety and resource integration and was argued to represent a linear production system as opposed to a dynamic system of exchange (Spring & Araujo, 2009; Ng, 2013). In acknowledging this, the literature review revealed a further five factors that would contribute toward our understanding of designing for high variety and use; agency in context, system boundaries (context), existing resources in context, institutions and contextual variety.

Finally, the literature review converged on servitization as context. The reasoning behind this was that this context provided an opportunity to study both the limitations of using a modularity for low variety frame within a context characterised by high variety and continuous change and the emerging phenomenon of designing for high variety. Toward the end of the servitization chapter, opportunities within servitization were presented. Here, three research questions were put forward alongside their relevant conceptual arguments. Based on the identification of an appropriate context for the research, a qualitative study was conducted using the themes identified within chapter 5 to analysis the data and present a number of propositions highlighting the limitations of a modularity for low variety frame and why designing for high variety a number of different requirements to designing for low variety.

12.2.2 Study one

Study one sought to understand the limitations of using a modularity for low variety frame when serving use where context is characterised by continuous change and high variety. In studying this phenomenon, it was possible to identify a number of reasons why designing for high variety has different requirements to designing for low variety. The reasons were put forward in a series of propositions that emphasise designing for high variety has different requirements because the entanglement of design and context introduces a number of different variables the organisation did not previously have to account for in their design activities. These were contextual variety, urgency, actor agency in use and actor generated institutions.

In addition, the results of study one also found a number of contradictions with existing modularity theory. Namely, that it is a strategy that helps organisations manage complexity inherent within systems. In this instance, it found that modularity is only able to contain complexity if the design change retains the functionality the architecture specifies and the module evolution is characterised by an improvement in performance of the existing functionality. However, if the design change integrates a functionality not originally frozen into the products architecture, the complexity is difficult to contain. In finding this, it was found that functional design changes post production may contribute to the service paradox as it threatens the firms viability through increased through life costs of managing the products architecture. However, it was noticed the use of digital technologies characterised by their unique affordance of digital materiality, could allow organisations to manage design complexity through the integration of digital resources.

12.2.3 Study two

The second study sought to build upon the qualitative study that preceded it and further study the use of a modularity for low variety frame in a context characterised by high variety and continuous change. Notably, the qualitative study showed that as design complexity increased, variety of use decreased. This suggested an increased design complexity might influence outcomes in use. However, the qualitative study was not able to conclusively show this. Therefore, the quantitative study sought to analyse the relationship between design change complexity and system viability as moderated by use complexity. In analysing this relationship, only one significant result was found. This was the moderating effect of use complexity on the relationship between design change complexity and system viability. The results were able to provide insight into the fact that to design for high variety, organisations need to approach the design of the value proposition fundamentally differently, with particular attention paid to the architecture and its ability to be flexible to change in use. Drawing insight from study one, a hybrid-architecture that benefits from the affordance of both material and digital resources would be a suitable way to serve use whilst being able to manage the complexity of the design changes. Thus making it viable from an organisations perspective to serve use.

12.2.4 Study three

Study three completed the theory building cycle of the thesis by building upon the foundation set by study one and two to test the efficacy of 3D printing on the system viability. It achieved this by simulating a dataset for testing the bootstrap estimates of the research model with the data based upon that used within the second study. The results of the hierarchical regression analyses on the 60 samples, 300 samples and the 1000 bootstrapped led to the rejection of H1 and H2, but their combined interaction effect possess an effect on the latter leading the author to support H2. By probing the interaction effects graphically, this study found that 3D printing implementation is most beneficial in the conditions studied across high and low use complexity and when design complexity is low. The main discussion point of this study was one that addressed conditions under which organisations would be best suited to adopt 3D printing for the purpose of supporting product instances. In deriving particular conditions within this case organisation, it provides one of the first empirical investigations that seeks to support particular use cases of 3D printing. In doing so, it combines findings from study one to suggest that organisations need to focus on the development of hybrid architectures that would allow them to support product instances and designing for high variety and that a key component of this is the identification of the boundary between scalability and variety.

12.2.5 Why does designing for high variety have different requirements to designing for low variety?

The purpose of this thesis was to answer the research question 'Why does designing for high variety have different requirements to designing for low variety? Based upon the literature review and three studies contained within this thesis, a number of answers emerged sequentially to provide a significant insight into the differences between the two design approaches.

12.2.5.1 Answer 1: Designing for high variety as a continuous process of resource adjustment

This answer is the coming together of the design and modularity literature and is visualised in figure 2.6 and is presented again here.

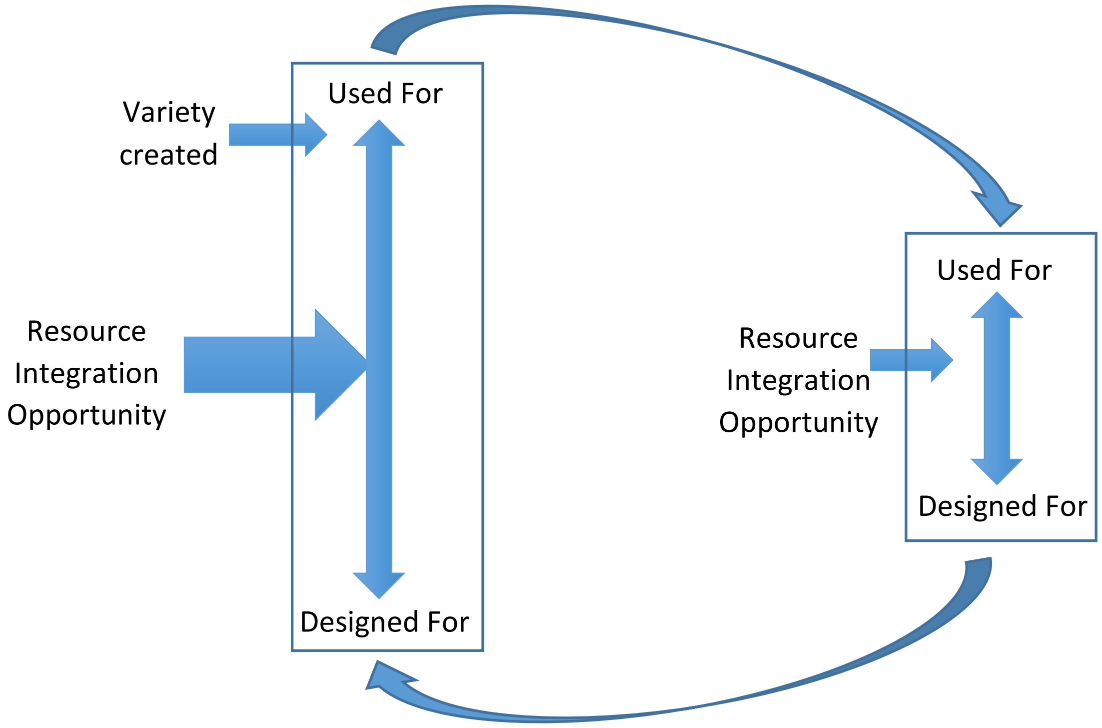

Figure 12.1. Illustration of designing for high variety.

In this framework, it can be seen that design and context are entangled and this has implications for the organisations design practices. Namely, the role of the organisation is to support the customers' value creating activities in use and constantly develop and propose resources that can be integrated at the point of use. The purpose of this is to create a value proposition that allows for a constant process of resource integration and adjustment so that the customer can close the gap between what the original resources were designed for and what they are being used for, given contextual variety has changed the resource requirements for the customer.

This answer alone is a development of existing design and modularity research. So far, research has primarily focussed on either designing for low variety or describing and illustrating the concept of designing for high variety. The figure presented her brings together the descriptions and illustrations into a single figure to present a more informative diagram that represents the purpose of designing for high variety, the entanglement of design and context and the role of the organisation in supporting the customers' value creating activities.

12.2.5.2 Answer 2: A framework for designing for high variety and modularity in context

This is a significant advance on the previous answer. It brings to the fore all relevant factors an organisation needs to account for when designing for high variety. Furthermore, it highlights how, if an organisation can align their design with the five primary constructs on the left side of the diagram, the customers' contextual experience can be modularised for the integration of resources in use. Whilst some of the factors were discussed within the figure presented in the first answer, S-D logic provides novel insight into additional factors an organisation needs to account for in their design activities. Thus, the full process from understanding the context, to value proposition design to resource integration are present within this framework and this significantly extends existing theories within design, modularity and OM.

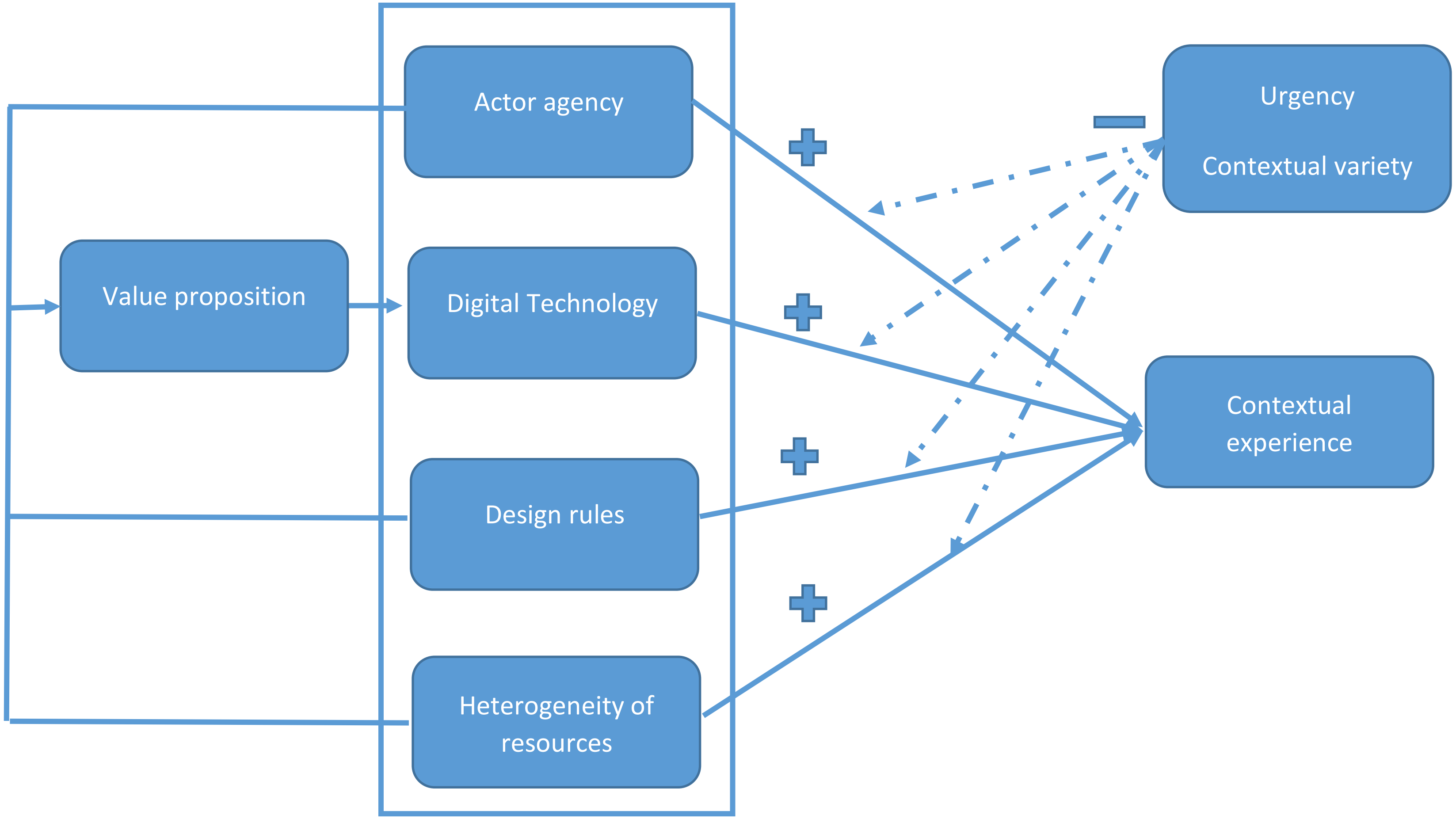

Figure 12.2. Conceptual Framework illustrating modularity in context

This is the framework that most helps understand why designing for high variety has different requirements to designing for low variety. It has been developed through a range of theoretical and practical insights and three empirical studies. This framework is considered to be the most developed of the two presented and indeed within the existing academic literature. It aligns well with existing work within design, modularity and S-D logic and highlights the increasingly important role of the operations manager is designing, creating and managing thin crossing points not only within the boundary of the firm, but also the customers' context of use. Furthermore, based on study one and three, it brings to the fore the increasingly important role of aligning 3D printing with the customers' context of use so that they can tailor, modify and adapt assets according to the use information they have and the agency they have in use, the institutions they are governed by and the others resources available to them in context.

Based upon the summary above, it is possible to conclude that this thesis has, at least partially, answered the question 'why does designing for high variety have different requirements to designing for low variety?'.

12.2.1 Contribution to Knowledge

Based on the discussion presented in section 8.1, the contribution to knowledge this thesis has made can be summarised as follows:

First, we identify a number of limitations with the existing modularity for low variety frame when used in a context characterised by high variety and continuous change. These findings contribute to the literature in four ways. First, it addresses the gap in the literature that calls for greater research surrounding the design of the physical asset within servitization. It does this by providing empirical support for Ng & Nurudupati (2010) who posit that new ways of thinking about design and production are needed within a servitized context that exhibits high variety in use, with a number of propositions presenting new ways organisations could approach design. It also provides empirical support for Ng & Briscoe (2012) who posit that the physical assets rigidity and reliance on existing design tools, theories and methods may be contributing toward the service paradox. Furthermore, it supports Garud et al (2008) by identifying design strategies focussed on complete designs are not suitable for contexts characterised by continuous change and high variety.

Second, the findings directly challenge the modularity literature that suggests modularity is a design strategy that allows modules to evolve autonomously without increasing complexity of the rest of the system (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Pil & Cohen, 2006). Namely, the findings showed how design changes that were not part of the original design specification increase the level of complexity within the products architecture. Thus, it suggests there is a condition upon which complexity can be contained and that is if the module that is evolving retains its original functionality (i.e., is an upgrade of the existing functionality). For example, the evolution of a hard disc drive to a solid state drive within the computer industry (Baldwin & Clark, 2000).

Third, the quantitative studies were some of the first to statistically examine the modularity for low variety frame within contexts characterised by high variety and continuous change. In addition, the benefits of 3D printing in absorbing variety and improving the viability of the customers' value creating activities were also statistically examined. Namely, the unit of analysis was not the firms manufacturing business unit but instead the customers' context of use. Whilst only one significant result was found in each of the studies, it provided a novel and timely quantitative investigation into the effect of design change complexity and use complexity on system viability (i.e., outcomes in use, value creation) and the benefits of 3D printing over traditional manufacturing in a designing for high variety context. However, several limitations of the studies did exist. These can be found in section 11.4.

Fourth, and most significantly, the findings presented within this thesis have led to the generation of a foundational theory for modularity-in-context that aids our understanding of designing for high variety. Specifically, this thesis combined knowledge from the existing literature (Schilling, 2000; Baldwin & Clark, 2000; Baldwin, 2008) with contemporary literature that re-evaluates the nature of value and exchange (Vargo & Lusch, 2004; 2016; Ng, 2013) to develop a conceptual framework that supports an organisations design activities when designing for high variety. Furthermore, in acknowledging service as a process as defined by S-D logic, it conceptualises modularity as enabling and coordinating the process of resource integration and finds compatibility with OM thinking. Therefore, this thesis makes a contribution to knowledge to the modularity literature in OM by re-aligning the focus of design and modularity on use and context, where design is seen as a process of resource integration.

Finally, this thesis has contributed to the development of a mid-range theory for S-D logic within OM. Namely, this thesis has drawn upon the foundational premises of S-D logic not only to reconceptualise design, but to alter the focus of design on resource integration and the customers' context of use. This theory was derived from a number of propositions in study one.

12.3 Managerial Implications

The research has a number of implications for managers involved in the design of servitized offerings with respect to the physical asset and product instances. It is important to note that whilst this research does not prescribe a set of specific design principles for the design of servitized value propositions, it seeks to influence practice by providing an alternate lens and way of thinking for operations managers. It is hoped this will help them understand what factors influence the design of their value proposition and the role they play within value creation for both the organisation and the customer.

Notably, design is critical to success for both customer's and organisations. Therefore, there are several implications emerging from this research.

First, it was found that designing for high variety and designing for low variety have very different philosophical underpinnings that affect how an organisation approaches design. Whilst Ng (2013) advocated all propositions should be designed for co-creation of value in use, this thesis has found two different approaches to design with one focussed on value in use and the other value in exchange. The main implication of this is in the theoretical contribution to designing for high variety as a process of resource integration. In presenting a conceptual framework in chapter 11, it helps organisations understand what affects their ability to design for high variety, the reinforcement effects between different factors and how they affect the end-to-end process of design and resource integration. These insights should help OEMs design their propositions for use. In particular, it brings to the fore the role non-technical factors such as actor agency, existing resources in context and institutions play in designing for high variety. In successfully designing for and around these factors, organisations should be more successful in their ability to design for high variety and integrate resources so that they can focus on product instances that are tailored, adapted and modified on mission by mission basis where outcomes may differ across contexts. There is much discussion about manufacturers and supply chains becoming more customer centric; this provides a means by which organisations may be able to deliver on that promise.

Second, it brings to the fore a new and increasingly important role of the operations manager. As discussed by Spring & Araujo (2009), identifying, designing and creating thin crossing points would likely become an increasingly important task for operations managers, especially within the context of product and process design. The findings of this study have found substantial evidence to suggest this is the case. Thus, a major implication for the organisation is not only the modularisation of their products and processes internal to the organisation, but also within and across service ecosystems so that resources can efficiently be integrated and exchanged within the customers' context of use for the purpose of value creation. This requires the organisation to have an appreciation of resources and structures that they are not necessarily in direct control of within their design activities. These include actor agency, value proposition design and institutions.

Third, whilst designing for high variety has emerged as a phenomenon of interest for practice, few empirically derived frameworks are available to operations managers. Whilst it does not provide a specific set of design characteristics that guide an organisation on how to design their offering, it provides a framework that illustrates the relationships between different variables that influence an organisations ability to design for high variety.

Finally, the first and third studies contribute towards a greater understanding to the use of 3D printing for managers. Namely, the studies show that 3D printing could be used to postpone the binding of form and function and in doing so, it could reduce the amount of complexity inherent in both use (i.e., 3D printing absorbs variety better) and design (i.e., because 3D printing is less constrained in what can be designed than traditional technology). Thus, 3D printing could allow organisations to create new business models that viably serve high variety contexts through the constant adaption, modification and tailoring of assets in use as and when latent needs emerge. This was shown in both the qualitative and quantitative studies. This would require a re-design of the physical asset and the supporting 3D printing services coupled to the physical asset.

12.4 Limitations and Future Research Opportunities

The research contained within this thesis is exploratory in nature. It sought to generate an understanding as to the phenomenon of interest and gain a greater understanding of said phenomenon for the purpose of building theory. However, whilst the research has contributed to knowledge, it is important to recognise the major limitations of this research.

There are three major limitations of this research and these provide an opportunity for future research.

First, the inability to conduct interviews with the customer as part of the qualitative research meant there was more of a firm emphasis on the findings even whilst the study sought to provide a balanced view of both provider and customer. Whilst the participants within the organisation provided novel insight into the customers' context of use through either working within close proximity of the customers use context or through previous experience as a member of the armed forces, their relationship with the organisation would potentially present a level of subconscious bias in their responses that could not be cross analysed against customer responses.

Second, a number of limitations existed in the quantitative study. First, whilst the interviews highlighted that the purpose of a UOR was to reduce the number of fatalities and injuries in use, it was not possible to guarantee the fatalities and injuries during the Afghanistan and Iraq campaigns happened whilst using the case organisations vehicles. Whilst the data represents fatalities and injuries during patrols that consisted of land vehicles, it was not possible to guarantee that the customer was inside the vehicle during the incident or, if they were, that it was a vehicle studied within this thesis. Whilst the proportion of their vehicles in the UK militaries fleet is high, allowing a degree of confidence to be instilled in the results, it is still not possible to guarantee that the fatality and injury rates increased or decreased as a result of the organisations design changes as information regarding which vehicles were involved in the incidents was often classified by the UK MoD. Furthermore, not having access to the customer meant potential sources of data that could compliment the current measure of system viability could not be accessed. For example, the customer, as opposed to the organisation, holds information regarding vehicle downtime and vehicle maintenance, and these could have been appropriate measures for system viability by showing the vehicle downtime was reduced following the design changes, allowing the customer to use them more often and more effectively. This provides an opportunity for future research should this data become publicly available or available to the research community. Third, use complexity is defined in terms of activities and tasks. Whilst relevant to the study of OM, the actual complexity of those tasks with respect to one another has not been calculated. In weighting each activity (i.e., each activity conducted by the customer) in terms of complexity (i.e., how complex each activity is individually) could enhance the granularity of the data and provide greater insights into the phenomenon. Whilst this thesis therefore contributes to a basic understanding of activities in use, there is scope for more detailed research going forward.

Third, whilst the qualitative study showed that engineers felt through life costs would increase due to the design change complexity, quantitative data for this did not exist at the time of the study. Further studies would benefit from quantitative data that explored the effect of the design changes on through life costs.

Fourth, the context of the study is a limitation. Within case study research, multiple cases are the preferred option for theory-building studies that can be generalised using the logic of replication across multiple case (Eisenhardt, 1989). Whilst this case has provided novel results and provided a chain of evidence that supports the validity and reliability of the results, it cannot be guaranteed that the research is applicable outside of the context within which it was studied due to the fact that it is a single case. Whilst the results may apply across the capital goods market, it is unclear whether their applicability to other industries can be established. Therefore, this thesis does not seek to claim generalisability beyond the context within which the results have been obtained. This limitation presents an opportunity for further research, with emphasis on exploring the conceptual framework within different contexts to check whether the results can be replicated across contexts.

Fifth, as organisations continue to develop their use of 3D printing, it would be useful to revisit the context of this study and collect data around design change complexity and 3D printing. Whilst the qualitative study was able to infer that it would reduce design change complexity, we were not able to statistically show this. Once the data is available, this provides an opportunity for future research.

12.5 Conclusion

This chapter has brought the thesis to a conclusion. It has discussed the findings of the literature review and empirical research against the overarching research objective and question. It has proposed a theoretical view of modularity in context that seeks to support our understanding of how to design for high variety. Finally, it has presented a number of contributions to knowledge of this work, managerial implications, limitations and future research.

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Appendices

Appendix 1 – Data sources

Data Source and Description	Date Published	Link to Source
Documents and Documentaries for Data Analysis		
Deloitte and DoD additive manufacturing report	2014	https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-defense-3d-printing/DUP_1064-3D-Opportunity-DoD_MASTER1.pdf
The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK	2013	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/255923/13-810-future-manufacturing-summary-report.pdf
Additive Manufacturing UK National Strategy: 2018-2025	2017	https://am-uk.org/additive-manufacturing-national-strategy-sets-establish-uk-world-leader/
Defence Standard 23-09: Generic Vehicle Architecture Issue 1	2010	http://portals.omg.org/dds/sites/default/files/DefStan_23_03_GVA_00000100.pdf
Future Character of Conflict	2015	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/486301/20151210-Archived_DCDC_FCOC.pdf
Operation TELIC – United Kingdom Military	2003	https://www.nao.org.uk/report/ministry-of-defence-operation-telic-united-kingdom-military-operations-in-iraq/

Operations in Iraq		
National Security Strategy and Strategic Defence and Security Review	2015	https://www.gov.uk/government/publications/national-security-strategy-and-strategic-defence-and-security-review-2015
The Rapid Procurement of Capability to Support Operations	2004	https://www.nao.org.uk/report/ministry-of-defence-the-rapid-procurement-of-capability-to-support-operations/
Centre for Defence Enterprise Themed Competition: additive manufacturing	2015	https://www.gov.uk/government/publications/cde-themed-competition-additive-manufacturing
Afghanistan: Cold War Warrior is no match for a Taliban bomb in the ground	2012	https://www.telegraph.co.uk/news/uknews/defence/9129151/Afghanistan-Cold-War-Warrior-is-no-match-for-a-Taliban-bomb-in-the-ground.html
Aircraft Technologies of the Future	Publication date N/A. Last accessed January 2017	https://www.baesystems.com/en-uk/feature/aircraft-technologies-of-the-future
CVR(T) Driver Instruction Manual	Updated 2018 edition	BAE Systems internal document
Ross Kemp in Afghanistan (series 1 and 2)	2012	Documentary DVD available for most retail outlets
Our War: Afghanistan	2011	https://www.bbc.co.uk/programmes/p00vhs86

Data Sources for System Viability Construct		
MoD National and Official Statistics by topic (search Afghanistan and Iraq fatalities and injuries)	Updated on a regular basis. Last accessed December 2017	https://www.gov.uk/government/publications/mod-national-and-official-statistics-by-topic/mod-national-and-official-statistics-by-topic
iCasualties	Updated regularly. Last accessed December 2017	http://icasualties.org/OEF/Index.aspx
Wikipedia – Iraq Casualties and fatalities	Updated regularly. Last accessed December 2017	https://en.wikipedia.org/wiki/Casualties_of_the_Iraq_War
Wikipedia – Afghanistan Casualties and fatalities	Updated regularly. Last accessed December 2017	https://en.wikipedia.org/wiki/British_Forces_casualties_in_Afghanistan_since_2001

Table 13.1. Data sources and links.

Appendix 2 – Case Study Protocol

1. Introduction

This case study protocol presents and described the main procedures to be followed during the case study.

2. Industry visits prior to data collection

Before the empirical data for each of the studies can be collected, the researcher needs to conduct a visit to the organisations offices and manufacturing units to gather background information, investigate possible information sources (e.g., organisational documents, annual reports, company history, defence standards etc.) and discuss with the industrial supervisors relevant information for the data collection phase. This step includes discussing the key informants for the data collection stages. The help of the industrial supervisors here is critical as they have a greater knowledge of internal business units and suitably knowledgeable individuals for each phase of data collection (e.g., platform champions and interviewees). It is important key informants are identified so the researcher can use them to address the research themes.

3. Off-site data collection arrangements

Following the initial visit, the researcher should liaise with the industrial supervisors to organise appropriate dates and sites (i.e., which of the organisations locations) to collect data from the key informants.

4. Data collection procedure (on-site)

Following identification of key informants in the previous site visit and the arrangement of times, dates and locations with the key informants, the researcher should proceed to collect data on-site with the key informants identified by the industrial supervisors.

In order to address the research question and research objective, data should be collected in the following major areas:

- 3D printing;
- Contextual experience;
- Institutions;
- Actor agency; and
- Design.

In seeking to collect data in these major areas, it is recommended the researcher aligns their questions with the unit of analysis and particular case being studied. Therefore, to draw insight into the major areas outlined above, the researcher should discuss the following with the interviewees:

- The differences between designing for high variety and designing for low variety;
- Urgent operational requirements (their purpose, their philosophy, what do they do, why are they needed); and
- 3D printing for resource reconfiguration (i.e., operational considerations, understanding different concerns based on who operates the value proposition).

The following table presents the themes to be address and the interview questions and documents used to address said themes. Whilst the questions directly address certain questions, responses may cross over to other themes and the researcher should be prepared to probe the interviewees answers to follow up on interesting responses for greater information and detail.

Theme to be addressed	Interview Question and documents to address themes
Urgent Operation Requirements	Background information - The Rapid Procurement of Capability to Support Operations - Vehicle tours - Read organisation and ministry of defence reports on UORs What would you say was the philosophy behind the UOR is? Do you think that the emergence of different threats and environmental conditions drove a lot of innovation around reconfiguring the vehicles?
3D printing	Background information - Deloitte and DoD additive manufacturing report - Centre for Defence Enterprise Themed Competition: additive manufacturing - Aircraft Technologies of the Future - Additive Manufacturing UK National

	Strategy: 2018-2025 - The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK How do you think 3D printing at the point of use could be used to absorb the variety of different threats and environmental conditions the customer is exposed to? How do you think 3D printing at the point of use would change the UOR process? What role do you see for 3D printing within the defence industry? What type of services could the organisation pursue if they could offer 3D printing at the point of use?
Contextual Experience	Background information - Future Character of Conflict - Afghanistan: Cold War Warrior is no match for a Taliban bomb in the ground - Operation TELIC – United Kingdom Military Operations in Iraq - National Security Strategy and Strategic Defence and Security Review What factors influence whether the customer can or cannot achieve their mission objectives during the use of the vehicle? What leads the MoD to raise a UOR? Would technology, such as 3D printing, extend BAE Systems reach to the customers' context of use and if so what are the implications of this?
Institutions	Background information - Discuss with industrial supervisors existing

	institutions, customer training, how do they train, do they train for specific vehicles, are they adaptable during conflict. Do you think there needs to be a higher level of involvement of industry at the point of use if 3D printing is offered as part of the organisations value proposition?
Actor Agency	Background information - CVR(T) Driver Instruction Manual - Discussions with industrial supervisors and retired army staff working for the case organisation to understand actor agency during conflicts. - Ross Kemp and BBC documentaries
Design	Background information - Defence Standard 23-09: Generic Vehicle Architecture Issue 1 - Vehicle tours - Presentation to discuss tank design and existing organisation design approaches What is the role and influence of modularity when a UOR is raised? Do you think the design of the asset has an effect on the service you can provide the customer in use? Could 3D printing influence the asset design and the type of service you provide for the customer in use? What do you think about 3D printing as an enabling technology for customers' to modify, tailor and adapt the assets at the point of use? How could 3D printing be used to rapidly

	reroll the assets for different missions?

Table 13.2. Interview questions and themes addressed.

5. Post data collection phase

Following data collection and analysis for each of the studies, a short PowerPoint presentation summarising the main findings should be presented to the industrial supervisors in order to receive feedback about the findings, with emphasis placed on any data that seems to contradict one another, validity and reliability of the results.

Appendix 3 – Ethical Approval Documents

It is important to note that when ethical approval was granted, the title of the research was different. Following agreement with the sponsoring organisation, EPSRC and WMG research degrees office, the PhD title was changed toward the end of the research when all data had been collected and analysed. The following figures present the ethics approval form and participant consent form. Transcripts and the extracted data (i.e., quotes used to inform the studies) can be requested from the individual who will liaise with the organisation to arrive at a decision as to whether a legitimate research reasons exists for accessing the raw data. During the initial discussions with the industrial supervisors, it was agreed that the raw data was not to be accessed by anyone beyond the researcher, their supervisors and the individual transcribing the interviews who had signed the appropriate documentation to agree to confidentiality and non-disclosure. The quotes used throughout this thesis were not found to contain any sensitive information in their condensed form and were allowed to be presented within the thesis.

9th April 2015

Warwick
Medical School

<u>PRIVATE</u>
Mr Phillip Davies
Service Systems Group
IIPSI
WMG
University of Warwick
Coventry
CV4 7AL

Dear Mr Davies,

Study Title and BSREC Reference: *The exploitation of additive layer manufacturing for the manufacture of components for armoured fighting vehicles* REGO-2015-1392

Thank you for submitting your revisions to the above-named project to the University of Warwick's Biomedical and Scientific Research Ethics Sub-Committee for approval.

I am pleased to confirm that approval is granted and your study may commence.

Please keep a copy of the signed version of this letter with your study documentation.

Yours sincerely

P.P. Graham Hewitt

Professor Scott Weich
Chair
Biomedical and Scientific
Research Ethics Sub-Committee

Biomedical and Scientific
Research Ethics Sub-Committee
A010 Medical School Building
Warwick Medical School,
Coventry, CV4 7AL.
Tel: 02476-528207
Email: BSREC@Warwick.ac.uk

Medical School Building
The University of Warwick
Coventry CV4 7AL United Kingdom
Tel: +44 (0)24 7657 4880
Fax: +44 (0)24 7652 8375

THE UNIVERSITY OF
WARWICK

Figure 13.1. Ethical approval form.

THE UNIVERSITY OF WARWICK

BIOMEDICAL AND SCIENTIFIC RESEARCH ETHICS COMMITTEE

CONSENT FORM

Study Number:

Participant Identification Number for this study:

Title of Project: The Exploitation of Additive Layer Manufacturing for the Manufacture of Components for Armoured Fighting Vehicles.

Name of Researcher(s): Philip Davies, supervised by Professor Irene Ng

Please initial all boxes

1. I confirm that I have read and understand the information sheet dated May 2015 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal rights or employment status being affected. ☐
3. I understand that relevant sections of my data collected during the study, may be looked at by individuals from The University of Warwick, from regulatory authorities where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records. ☐
4. I agree to the interview being recorded ☐
5. I understand that the data may be used in subsequent studies. ☐
6. I agree to take part in the above study. ☐

________________	________________	________________
Name of Participant	Date	Signature

Philip Davies

________________	________________	________________
Name of Person taking consent	Date	Signature

Philip Davies REGO-2015-1392 VERSION 2

Page 1 of 1

Figure 13.2. Consent form for participants.

Appendix 4 – Platform Matrices

Presented within this appendices are the matrices for the Bulldog and CVR(T) platforms. Specifically, the first and last matrices (i.e., before and after the conflicts the UK Military was involved in) are presented for Bulldog 4 and CVR(T) Scimitar. A complete set of matrices are available upon request and subject to specific conditions of the sponsoring organisation.

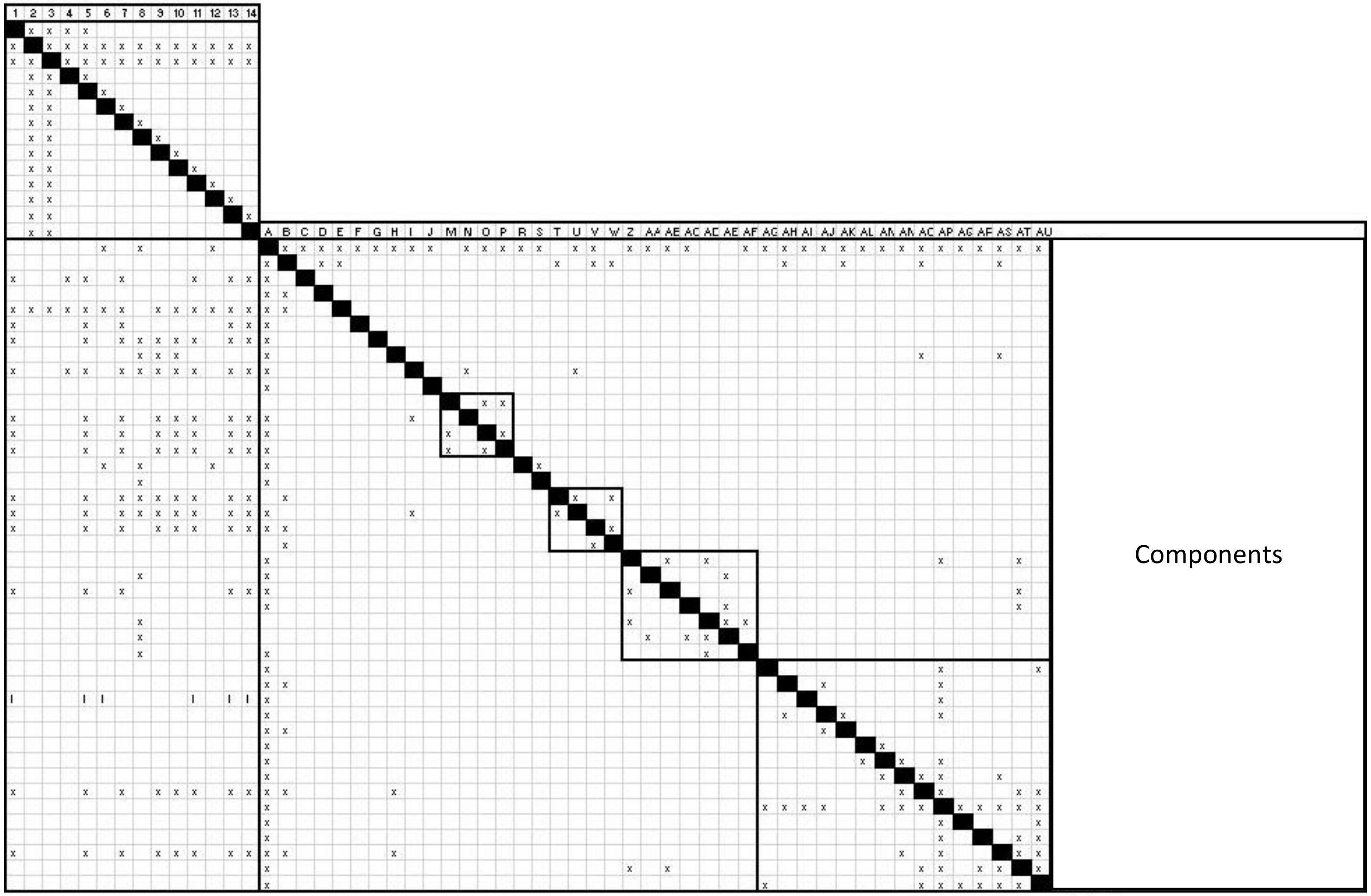

Figure 13.3. Bulldog 4 DMM pre-conflicts.

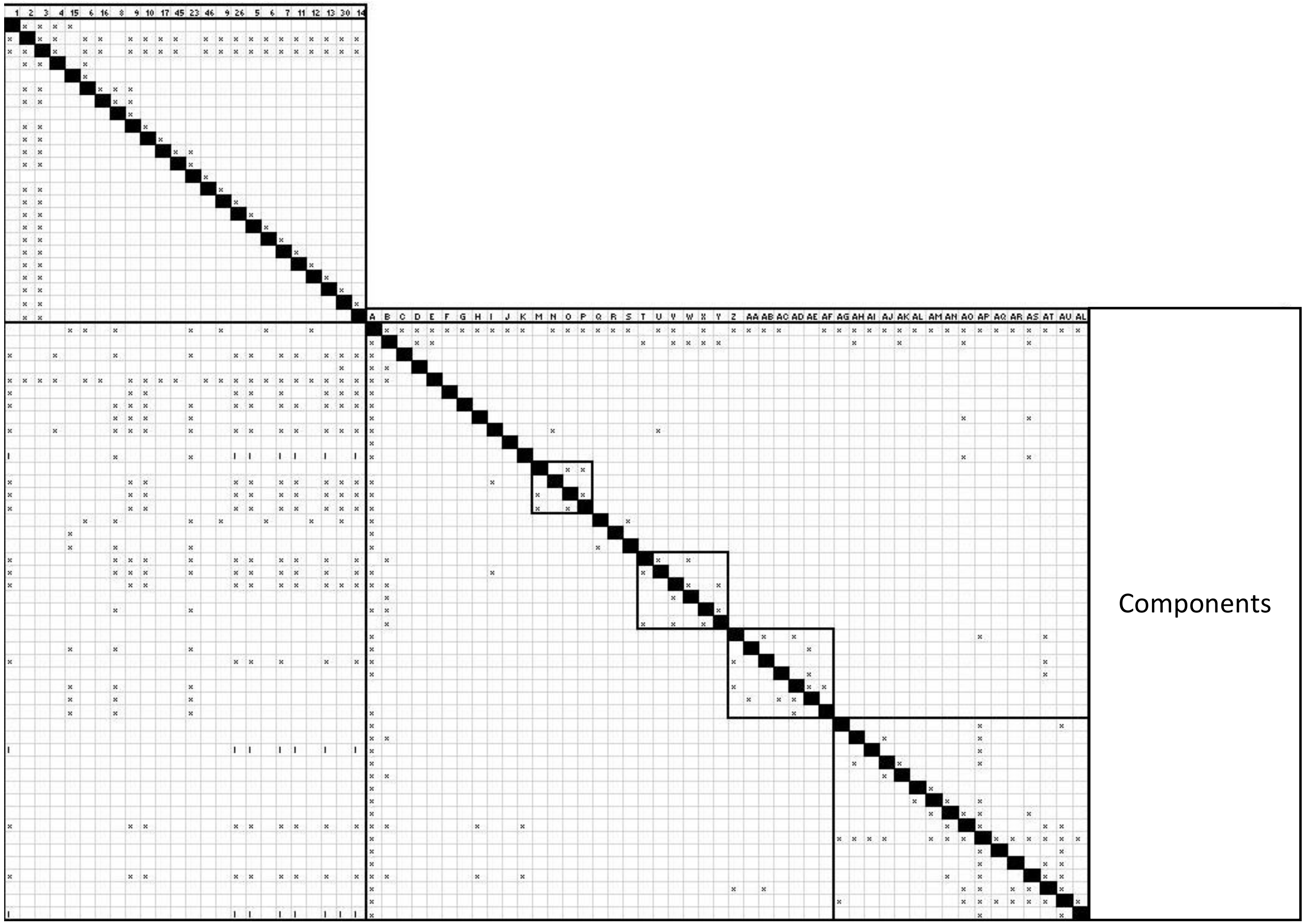

Figure 13.4. Bulldog 4 DMM post-conflicts.

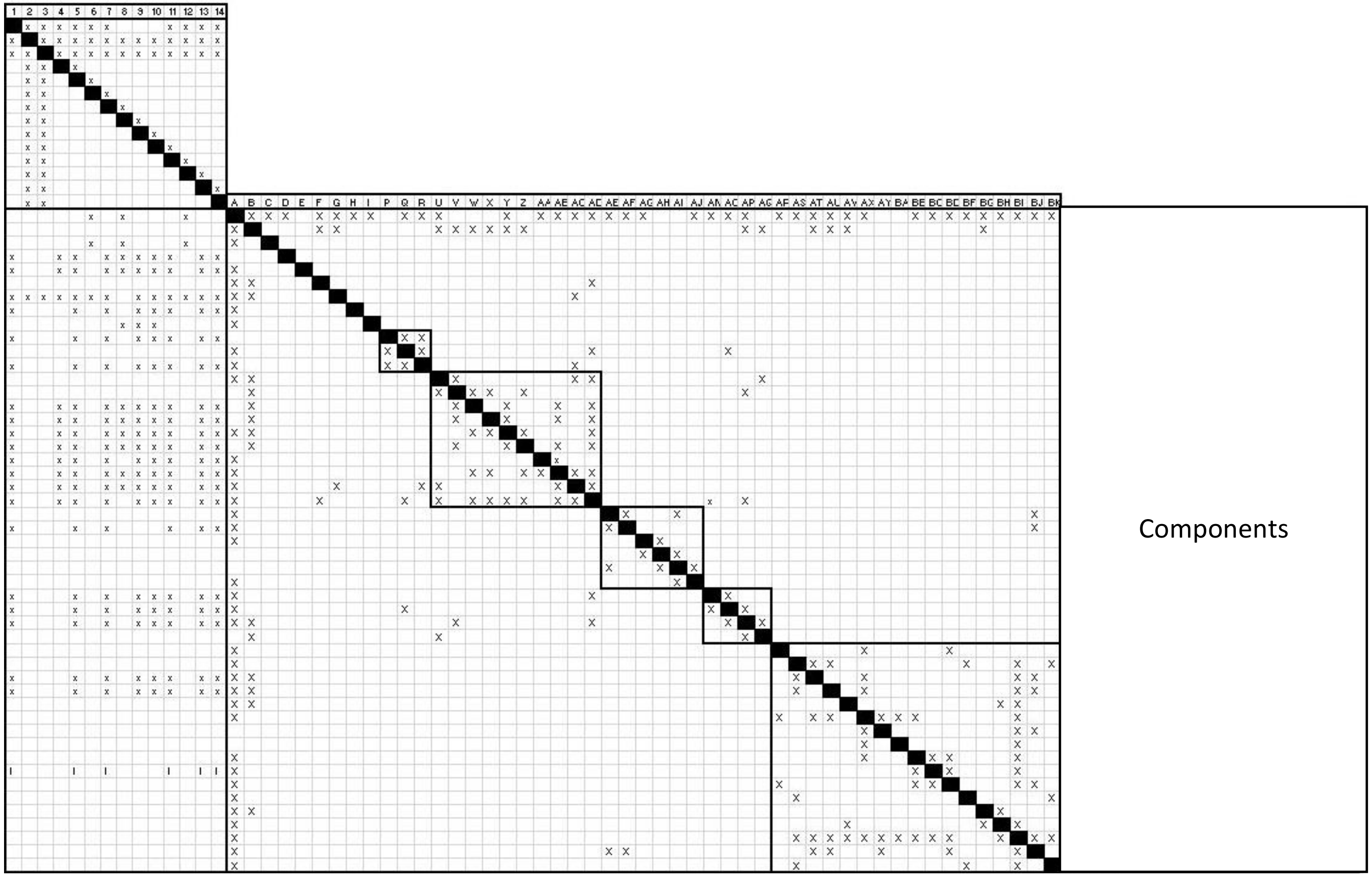

Figure 13.5. CVR(T) Scimitar DMM pre-conflicts.

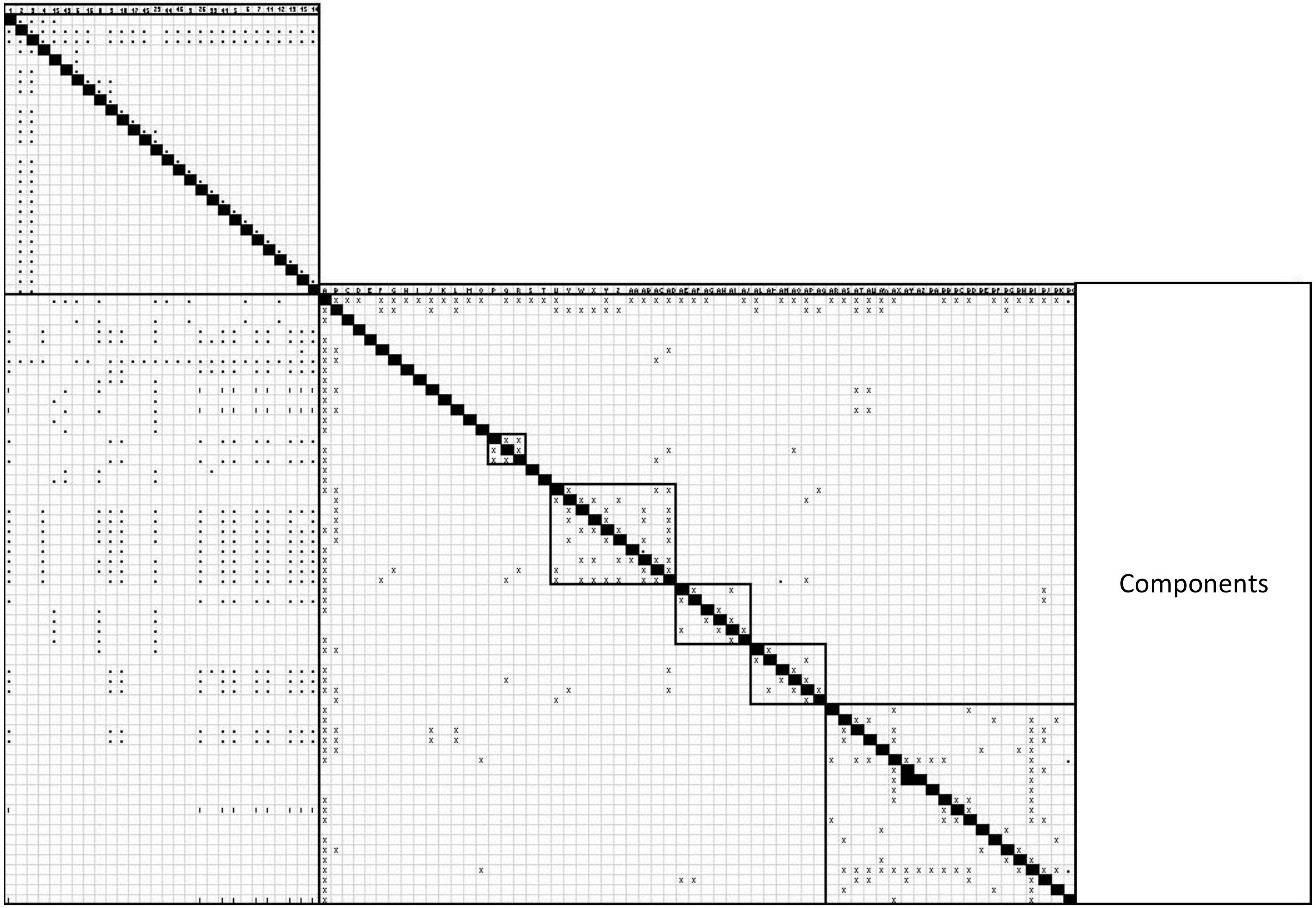

Figure 13.6. CVR(T) Scimitar DMM post-conflicts.

Appendix 5 – Growth Gradient Analysis

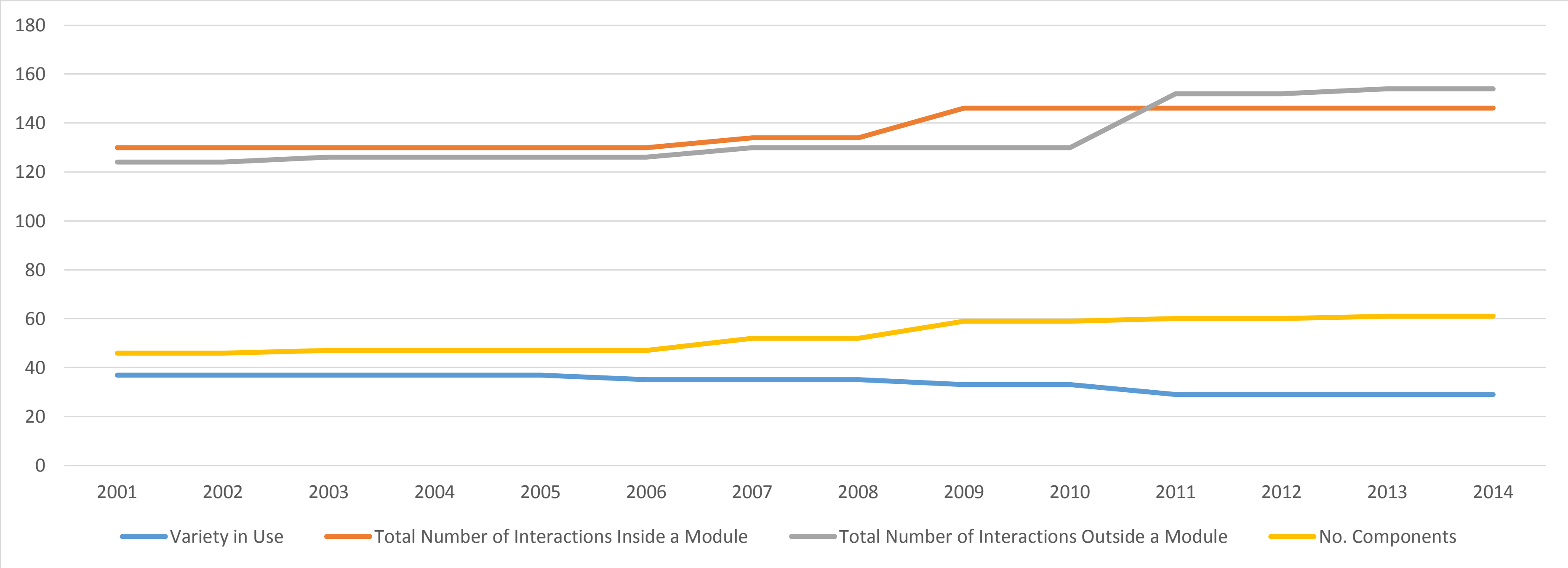

Figure 13.7. CVR(T) Scimitar growth gradient analysis.

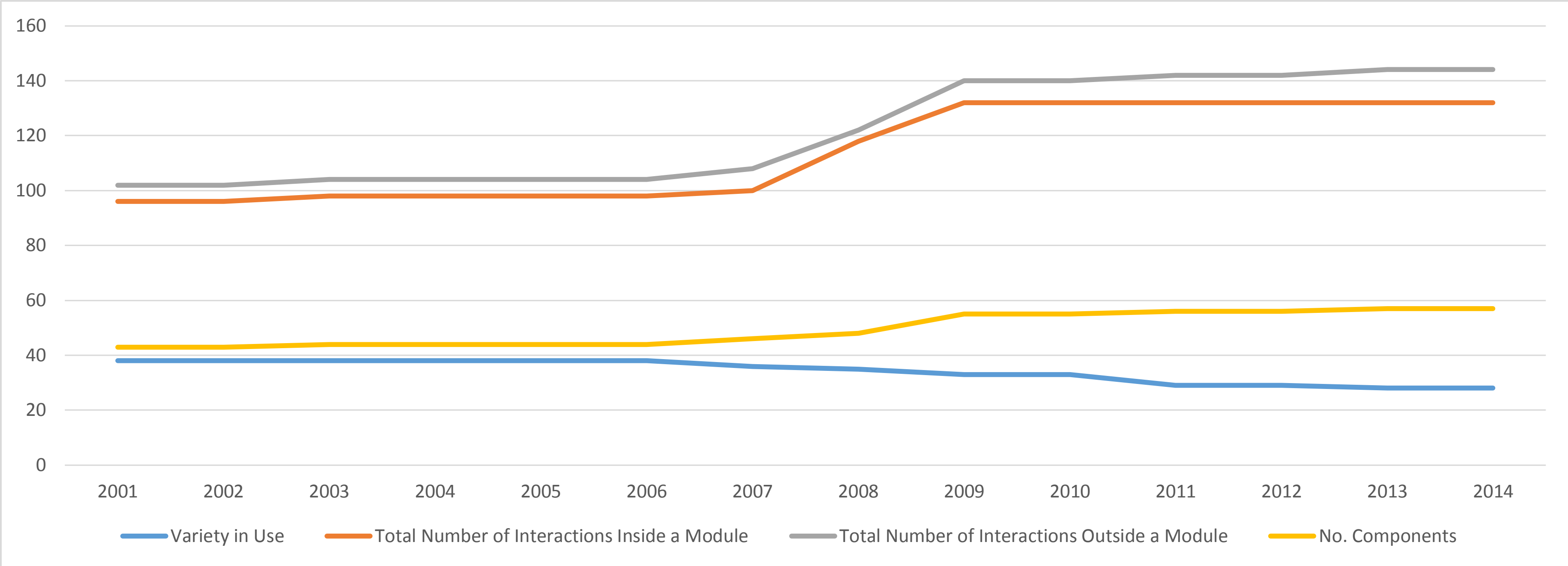

Figure 13.8. CVR(T) Spartan growth gradient analysis.

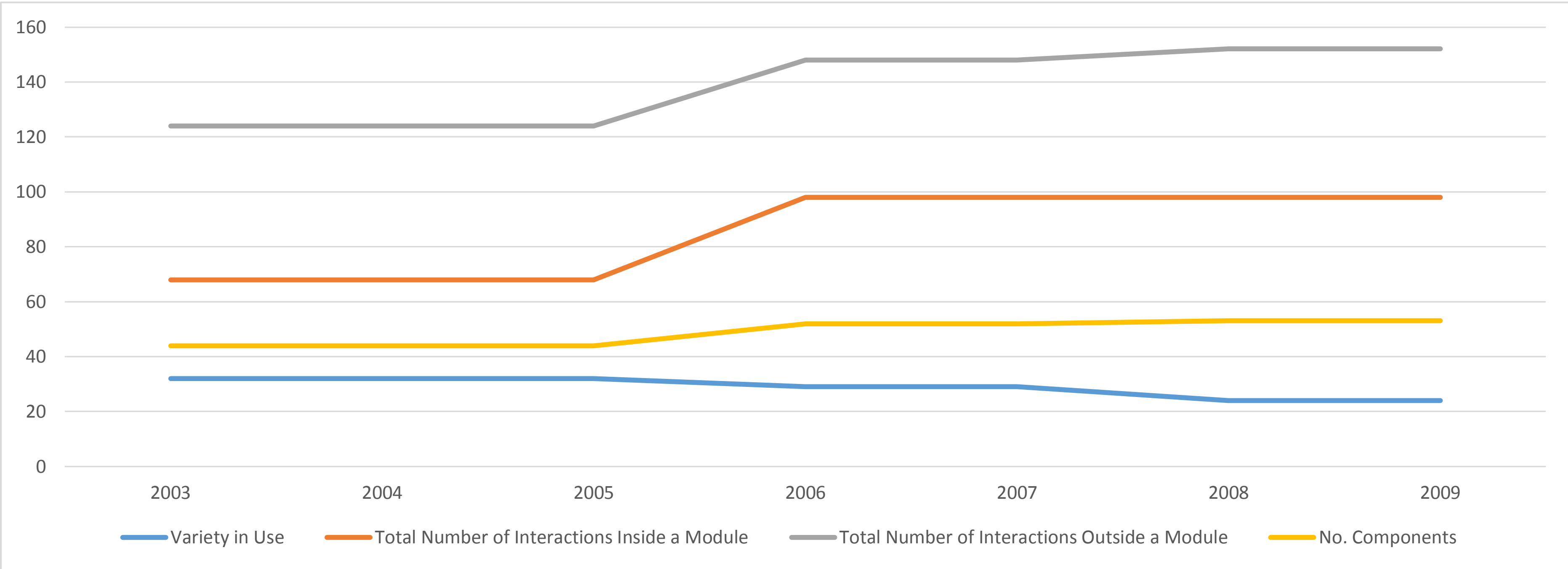

Figure 13.9. Bulldog 2 growth gradient analysis.

Appendix 6 – Activities for Activity Structure Matrix

1 – Transit to mission

2 – Communicate to crew

3 – Communicate to group

4 – Operate heads out

5 – Arrive at mission checkpoint

6 – Troops exit from rear

7 – Position vehicles to support troops

8 – Enemy engage the convoy

9 – Troops return fire from weapons station

10 –Troops suppress enemy

11 – Wait for troops to return

12 – Troops enter from rear

13 – Return to base

14 – Arrive at base

15 – Explosion under vehicle

16 – Troops form force protection screen

17 – Injured assessed

18 – Air evacuation called

19 – Troops make air evacuation aware of location

20 – Air evacuation lands

21 – Air evacuation tends to injured

22 – Air evacuation leaves

23– Recovery team attends to vehicle off road

24 – Vehicle declared off road

25 – Emergency recovery team recovers vehicle

26 – Continue to transit to mission

27 – Arrive at overnight station

28 – Keep watch overnight

29 – Continue to transit in daylight

30 – Continue through the night

31 - Enemy hit vehicle gunner

32 – Vehicle catches fire

33 – Troops extinguish fire

34 – Fire extinguished

35 – Vehicle drives into ditch

36 – Recovery team loops winch around vehicle

37 – Vehicle toward back onto road

38 - Winch loop repeated

39- Commander identifies strung wire

40 – Commander communicates with crew to operate heads in

41 – Convoy move out of compound

42 – Commander communicates with crew to operate heads in

43 – Vehicle rolls over

44 – Vehicle righted

45 – Injured treated

46 – Vehicle declared road worthy

47 – Troops return fire from remote weapons system

48 – Remote weapons system supresses’ enemy

Appendix 7 – Coded items for System Viability Construct

System Viability Construct
Yes, definitely. From what I understand, you know, in a number of ways I think certain modifications to some of the vehicles to minimise the risks of, you know, the occupants. (INT)
There are, I mean generally, urgent operation the key is in the title really. The vehicles are on operations and, you know, we've done quite a few protection ones, we've had vehicles that have been hit, vehicles that have been overmatched and they'll come back and say, you know, "Unfortunately we've had casualties and we need an answer," and they could be anything from protection to additional counter measures, to weapons, we've done many, many of them over the years now, increased power. (INT)
…so by the nature of a UOR it starts with a problem and that problem is urgent because it's encountered in an operational conflict and, therefore, if you don't solve it it could lead to loss of life. (INT)
To save life. (INT)
So all the UORs were things like better situational awareness, the ability to drive in confined spaces, better vision for the driver, so more periscopes attached, that came out of Kosovo, one of the operations out there. I think they lost a driver in that instance. So that put the … on Warriors. (INT)

But if you think about your layers of protection, your first layer is don't be there. Then it's don't be seen. Then it's don't be hit. If you're hit, don't be defeated or penetrated, and if you're penetrated, don't be killed. (INT)
So the nice mathematical thing of reducing the … on the vehicle to hopefully cause less damage, kill nobody or kill less people, that's what the support line is there to do, it's to try and narrow that cone end off, even though you're bleeding or you're defeated, and reduce some of those secondary effects. (INT)
…because the political drive is that they can't lose people. So if you talk to the military guys, militarily they can lose people, the army is configured to lose people, it's configured to go to war, it's configured, unfortunately, for men to die. Militarily they can sustain really quite heavy losses. Politically nowadays they can't. (INT)

Table 13.3. Coded items for system viability construct.

Appendix 8 – Hierarchical Linear Regression Outputs

This section presents the major outputs of the statistical analysis performed within study two.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.500	.198		12.644	.000
	Bulldog 2	-.365	.331	-.167	-1.102	.275
	Bulldog 4	-.359	.356	-.149	-1.006	.319
	CVR(T) Scimitar	.245	.253	.172	.968	.337
	CVR(T) Spartan	.189	.253	.133	.747	.458
	CVR(T) Samson	.252	.253	.177	.993	.325
2	(Constant)	2.418	.225		10.728	.000
	Bulldog 2	-.425	.341	-.195	-1.245	.219
	Bulldog 4	-.400	.362	-.166	-1.104	.274
	CVR(T) Scimitar	.255	.255	.179	1.001	.322
	CVR(T) Spartan	.228	.259	.160	.879	.383
	CVR(T) Samson	.246	.255	.173	.968	.338
	loguc	.223	.290	.109	.768	.446

3	(Constant)	2.362	.320		7.386	.000
	Bulldog 2	-.410	.349	-.188	-1.175	.246
	Bulldog 4	-.398	.365	-.165	-1.089	.281
	CVR(T) Scimitar	.244	.261	.171	.937	.353
	CVR(T) Spartan	.220	.264	.155	.834	.408
	CVR(T) Samson	.244	.257	.171	.949	.347
	loguc	.202	.304	.099	.665	.509
	logdc	.292	1.164	.035	.251	.803
4	(Constant)	3.018	.319		9.470	.000
	Bulldog 2	.332	.351	.152	.945	.349
	Bulldog 4	.025	.333	.011	.076	.940
	CVR(T) Scimitar	.651	.246	.457	2.642	.011
	CVR(T) Spartan	.562	.243	.395	2.312	.025
	CVR(T) Samson	.521	.233	.366	2.238	.030
	loguc	-4.005	1.033	-1.951	-3.878	.000
	logdc	-3.435	1.344	-.407	-2.556	.014
	intucdc	16.030	3.804	2.196	4.214	.000

Table 13.4. Standardised and unstandardised coefficients from HLRM.

Coefficients[a]

Model		Collinearity Statistics Tolerance	VIF
1	(Constant)		
	Bulldog 2	.701	1.426
	Bulldog 4	.742	1.348
	CVR(T) Scimitar	.510	1.959
	CVR(T) Spartan	.510	1.959
	CVR(T) Samson	.510	1.959
2	(Constant)		
	Bulldog 2	.665	1.505
	Bulldog 4	.726	1.378
	CVR(T) Scimitar	.509	1.964
	CVR(T) Spartan	.491	2.035
	CVR(T) Samson	.510	1.961
	loguc	.817	1.224
3	(Constant)		
	Bulldog 2	.646	1.548

	Bulldog 4	.725	1.379
	CVR(T) Scimitar	.495	2.019
	CVR(T) Spartan	.484	2.066
	CVR(T) Samson	.509	1.963
	loguc	.757	1.320
	logdc	.873	1.145
4	(Constant)		
	Bulldog 2	.484	2.068
	Bulldog 4	.659	1.517
	CVR(T) Scimitar	.419	2.385
	CVR(T) Spartan	.430	2.326
	CVR(T) Samson	.469	2.134
	loguc	.050	20.156
	logdc	.495	2.020
	intucdc	.046	21.619

Table 13.5. Collinearity and VIF outputs from HLRM.

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Bulldog 2	Bulldog 4
1	1	1.922	1.000	.04	.02	.01
	2	1.000	1.386	.00	.03	.02
	3	1.000	1.386	.00	.12	.01
	4	1.000	1.386	.00	.41	.03
	5	1.000	1.386	.00	.02	.57
	6	.078	4.962	.96	.40	.35
2	1	2.621	1.000	.02	.01	.01
	2	1.055	1.576	.00	.18	.07
	3	1.000	1.619	.00	.01	.23
	4	1.000	1.619	.00	.03	.07
	5	1.000	1.619	.00	.25	.21
	6	.253	3.216	.02	.28	.17
	7	.070	6.115	.96	.23	.23
3	1	3.522	1.000	.00	.01	.00
	2	1.082	1.804	.00	.21	.07

	3	1.001	1.876	.00	.11	.03
	4	1.000	1.877	.00	.08	.47
	5	1.000	1.877	.00	.08	.01
	6	.254	3.721	.01	.27	.16
	7	.102	5.864	.05	.11	.17
	8	.038	9.675	.94	.15	.07
4	1	4.263	1.000	.00	.00	.00
	2	1.135	1.938	.00	.09	.05
	3	1.003	2.062	.00	.21	.04
	4	1.001	2.064	.00	.01	.00
	5	1.000	2.065	.00	.02	.42
	6	.445	3.097	.01	.15	.14
	7	.103	6.447	.04	.07	.14
	8	.043	9.995	.54	.22	.12
	9	.009	22.071	.42	.23	.08

Table 13.6. Collinearity Diagnostics for HLRM.

Appendix 9 – Output from Statistical Analysis of Study Three

Coefficients[a]

Model		Collinearity Statistics Tolerance	VIF
1	(Constant)		
	D1	.701	1.426
	D2	.742	1.348
	D3	.510	1.959
	D4	.510	1.959
	D5	.510	1.959
2	(Constant)		
	D1	.673	1.485
	D2	.721	1.387
	D3	.510	1.960
	D4	.505	1.982
	D5	.508	1.969
	loguc	.880	1.137
3	(Constant)		

	D1	.662	1.510
	D2	.721	1.387
	D3	.499	2.002
	D4	.501	1.995
	D5	.507	1.972
	loguc	.865	1.156
	logdc	.926	1.079
4	(Constant)		
	D1	.563	1.776
	D2	.679	1.473
	D3	.447	2.239
	D4	.456	2.192
	D5	.483	2.069
	loguc	.063	15.954
	logdc	.543	1.843
	intucdc	.060	16.798

Table 13.7. Collinearity statistics and diagnostic results for study three statistics.